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Sustainability aspects of Bauxite and Aluminium

Climate change, Environmental, Socio-Economic and Circular Economy considerations

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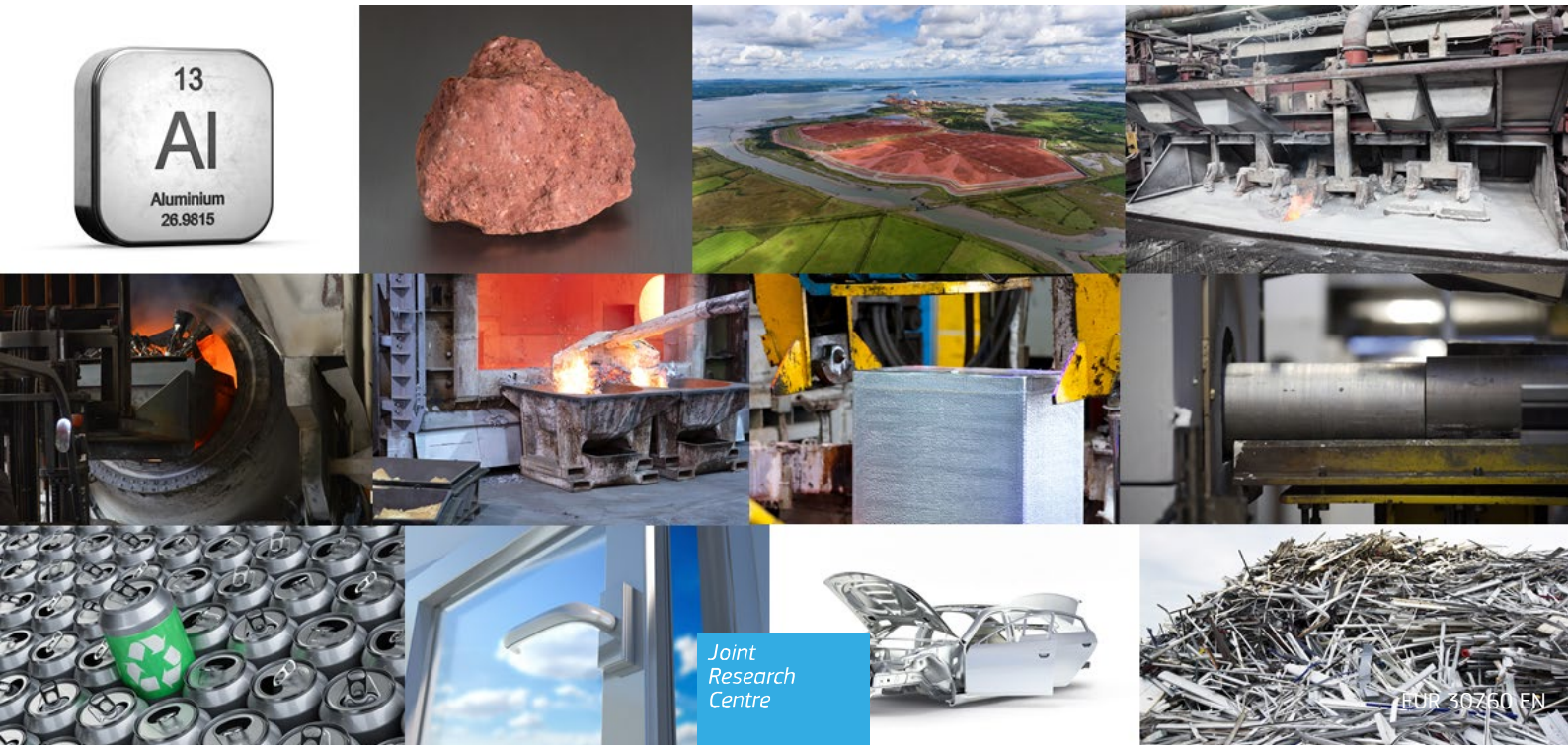

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Abstract

Aluminium has a significant industrial base in the EU and strong links with many industrial ecosystems. As sustainability has come to the forefront of public and policy attention, factors to evaluate the sustainability of bauxite and aluminium's supply and use can be classified in Climate Change, Environmental, Social, Circular Economy and Economic aspects.

Aluminium is one of the most carbon-intensive industrial metals to produce. Greenhouse gas emissions during aluminium production is the greatest sustainability challenge for the aluminium industry. Substantial progress has been attained in the last decades in reducing process emissions, and in Europe, the domestic aluminium production has achieved a lower carbon footprint than the global average. However, due to the increasing penetration of high-carbon aluminium imports, this achievement is not reflected in a lower footprint of the aluminium used in Europe. As the carbon intensity of primary aluminium production relies mainly on electricity production's carbon footprint, the greening of the grid energy mix is the key to driving down the carbon count per tonne of metal. Furthermore, secondary aluminium production has enormous carbon benefits as only a tiny fraction of the energy to produce primary metal is required.

At the same time, aluminium is an enabler to other sectors to decrease their carbon footprints due to its lightweight and strength. Energy efficiency and low-carbon applications are expected to be the drivers of aluminium's growing demand. Both primary and recycled metal will be needed to meet demand in the future.

The large land area requirement for bauxite mining within or close to nature protected areas and tropical forests and/or indigenous lands is the main challenge that bauxite mining industry worldwide has to address in order to reduce impacts on biodiversity and local communities. Another critical issue in the environmental domain of aluminium — but also in the social and circular economy — is the management of bauxite residues (red mud) generated during the alkaline digestion of bauxite ore in alumina production. Additional environmental challenges can derive from bauxite mines' location in water-scarce areas or nature protected areas, as well as from the poor environmental performance and high natural hazards risk in bauxite supplying countries.

The main emission and resource consumption levels in each stage of the aluminium value chain are also outlined in the report, combined with results from Life Cycle Assessment studies conducted by international aluminium organisations.

The report also discusses the achieved end-of-life recycling indicators and the role of aluminium recycling in the security of supply and climate change mitigation. An increase in aluminium recycling rates will enhance the Union's strategic autonomy in view of the projected increased demand in the next decades. It will also enable a lower carbon footprint of aluminium production in the EU. The aluminium scrap leaving the Union and the indirect downcycling of wrought alloys to aluminium castings are among the challenges to overcome for higher circularity.

Insights given on the social perspective of the aluminium industry include occupational health and safety, environmental conflicts across the globe, international initiatives to improve the industry's sustainability performance, and governance in bauxite producing countries. An identified risk for the EU aluminium sector's sustainability performance is the fragile governance in the leading bauxite supplier to the EU (Guinea). Bauxite exploration and new mine development, and the management of massive volumes of bauxite residues cause several conflicts worldwide.

Concerning the industry's socio-economic contribution, the European industry generates revenues and value added of billion euros and contributes with thousands of jobs to the EU economy. The report looks at the economic dimension of the EU aluminium industry through data for production value, value added, employment, and investments.

Executive Summary

Aluminium is the second most widely used metal in modern society. It is a lightweight, highly workable, and versatile metal. The aluminium value chain stretches from bauxite mining to alumina, and from primary production to semi-finished products, end-use products and ultimately to recycling. The following sections resume the key findings related to aluminium's value chain sustainability.

Climate Change

Aluminium's unique properties enable other sectors to reduce their carbon footprint. Applications in a low-carbon and circular economy include light-weighting in mobility and energy efficiency in construction. Aluminium is one of the key industrial metals for unfolding the green transition for its widespread use across energy technologies; in particular, the vast majority of growth in demand for aluminium is tied to solar PV panels.

Primary aluminium production is highly energy-intensive, responsible for considerable greenhouse gas (GHG) emissions. The smelting (electrolysis) process requires significant amounts of electricity to break the oxygen-aluminium bond of the input material (alumina); therefore, it is responsible for the major part of the carbon footprint of primary aluminium. In this respect, the availability of climate-neutral electricity determines the carbon footprint of aluminium smelters. Hence, the greening of the power mix is the driver for effectively lowering the carbon intensity in Europe by 2050. Moreover, the anode consumption during electrolysis and the thermal energy consumed in alumina's calcination are also sizable GHG contributors.

The primary aluminium produced in Europe has a lower carbon footprint than the global average, which decreased significantly by 21% from 2010 to 2015. The renewables' share in the energy mix for primary aluminium in EU+UK+EFTA has increased between 2010 and 2015 and the carbon footprint can drop further as the European power sector decarbonises. However, the rising penetration of imports in the EU combined with a lower imports' environmental performance does not allow a substantial improvement in the overall environmental impact of primary aluminium consumed domestically. For instance, smelters in China, where coal is the predominant power source, have almost a three times higher carbon footprint than the European (EU+UK+EFTA) ones despite the major strides in improving their energy efficiency in the last years.

The absolute direct (process) GHG emissions from primary aluminium production have decreased substantially in the EU from 1990 to 2018, mainly because of the remarkable decline of Perfluorocarbon (PFC) emissions. Innovation for the development of breakthrough low-carbon smelting technologies is needed for a drastic reduction of process (direct) emissions.

Other Environmental aspects

Concerning bauxite's geology and mining practices, the most concerning aspect for the environmental hazard potential of mining sites and mined bauxite is the mine type as bauxite mines are almost entirely open-pit, requiring access to large land zones. Moreover, the large lands required are often near or close to areas of high conservation value in terms of biodiversity and/or indigenous lands, such as tropical forests. For example, bauxite mining is the most significant contributor to Brazilian Amazon's deforestation within mining leases. Still, post-mining rehabilitation of vegetation is reported as relatively easy.

The EU supply of bauxite originates from countries where the proportion of mine sites within areas of high-water stress is higher than the world average. 84% of the capacity of operating bauxite mines in the EU sourcing countries is located in places with water stress ranging from high to extremely high. In comparison, the world average within areas of 'high' and 'extremely high' water risk is 40%. At the same time, it is estimated that 17% of the operating mining capacity in the EU supplying countries is located within nature protected areas versus the world average of 8%. Operating bauxite mines in the EU are predominantly found within areas of the Natura 2000 network. However, these are mostly underground, so the impacts are expected of less intensity. Also, the group of countries supplying bauxite to the EU have lower environmental performance than the world average of bauxite supply, and this is mainly due to Guinea's very low value.

Operating installations in the EU with activities in alumina production, anode production, primary and secondary aluminium production, salt slag recycling, as well as in coating and printing of flat-rolled aluminium sheets, aerosols, collapsible tubes, 2-piece drawn aluminium cans, and packaging closures are currently (February

2021) covered by Best available techniques (BAT) conclusions in accordance with the Industrial Emissions Directive (Chapter II of Directive 2010/75/EU on industrial emissions).

The production of electricity is the most significant contributor to the environmental impacts of primary aluminium production for every impact category, except for abiotic depletion. The European industry generally has lower consumption and emission levels than the world average for each process in the aluminium value chain, i.e. alumina refining, anode production, aluminium smelting and secondary production (no European-specific data exist for bauxite mining). Primary aluminium production has higher impacts than secondary aluminium production for all impact categories.

Finally, registry data from the REACH ([1]) and CLP ([2]) registries ascertain no risks from aluminium metal exposure for humans and the environment.

Social Sustainability aspects

Guinea, the leading supplier of bauxite for the EU (providing 58% of the EU sourcing in 2018) has a low governance level.

Similarly, Sierra Leone, supplying 11% of the EU sourcing, has low governance levels, especially for government effectiveness and regulatory quality. These two countries also have a poor performance in other social indicators like percentage of child labour, fragile state, conflict risk and Human Development Index.

Concerning Occupational Health and Safety (OHS) in the aluminium industry, data from the International Aluminium Institute reveal that the aluminium industry worldwide has achieved a marked improvement in OHS. The accidents rate in primary aluminium smelters has had the most remarkable reduction in the last two decades.

Concerning the EU aluminium industry, certifications of OHS management systems have increased considerably, and significant improvements have been achieved in terms of reduction of accidents at work from 1997 to 2008.

The Aluminium Stewardship Initiative (ASI) is a large organization devoted to improving the sustainability of the aluminium industry. So far, companies holding 30% of the total bauxite production capacity and 11% of the total primary aluminium smelting capacity are certified according to ASI Performance Standards. The increasing adoption of certifications are supporting the sector in enhancing its environmental performance, social impacts in local communities and transparency.

The analysis of environmental conflicts worldwide, as reported in the Environmental Justice Atlas dataset across the aluminium value chain, shows that land use for bauxite exploration and new mine development is the most frequent cause of conflicts. The management of bauxite residues and related energy projects (e.g. construction of dams) to aluminium production are other recurring roots of local conflicts and oppositions among the cases documented in the Atlas. The mounting number of reported conflicts over the last decades related to bauxite exploration and mining, alumina refineries and primary aluminium production peaked in 2017, but a de-escalation is observed afterwards.

The bauxite mining sector has a prominent role in the Guinean economy, and it led to the creation of mining towns in the 60s and 70s. In fact, bauxite production in the country has grown considerably in recent years, exporting mainly to China (74%) and the EU (17%). Even considering that Guinea has improved its governance in the management of natural resources, according to the Resources Governance Index trend, nonetheless negative impacts related to mining projects were described in a Human Rights Watch report. Focusing on Guinea's two largest mining projects, it highlighted the profound human rights consequences to local

([1]) https://ec.europa.eu/environment/chemicals/reach/reach_en.htm
([2]) https://echa.europa.eu/regulations/clp/understanding-clp

communities that live closest to the fast-growing bauxite mining industry, such as undermined air quality, damage to water sources, loss of farmlands, etc.

Circular Economy aspects

Aluminium's circular economy credentials are significant. Resource gains are particularly large, and recycling plays a vital role in meeting current and future demand contributing to the EU's security of supply for unwrought aluminium.

Recycled aluminium represents one-third of the aluminium metal supply and two-thirds of all the aluminium currently produced in the EU. However, primary production will still be needed in the foreseeable future as secondary aluminium production is limited by scrap availability. Moreover, aluminium recycling sharply reduces carbon emissions compared to new production. Thereby, the shift to secondary production in Europe can achieve substantial savings in GHG emissions.

Recycling rates for post-consumer aluminium scrap in Europe are comparatively higher than in the other regions. Collection rates achieved in Europe are over 90% for aluminium used in transport and construction, while recycling of beverage cans achieved a record level in 2018. Yet, 21% of end-of-life aluminium in Europe is not collected for recycling. In order to enable a larger share of secondary production and obtain all the potential gains in GHG emissions, circularity has to be enhanced through higher collection rates from consumer products (achieved by e.g. improved product design), advanced scrap pretreatment to optimise scrap segregation to avoid incompatible alloys with product specifications and limit indirect downcycling of wrought alloys to aluminium castings. Also, decreasing scrap outflows outside the EU will improve circularity; since 2009, significant amounts of recyclable aluminium scrap are leaving the EU and the Asian countries are mostly capturing this valuable European resource.

Economic impact

The aluminium sector plays a significant role in the EU's economy. EU's wider aluminium industry (NACE ([3]) 24.42 'Aluminium production' and NACE 24.53 'Casting of light metals') includes over 2,800 companies in primary and secondary production route and production of semi-finished products. The overall production value was over 61 billion EUR in 2018, and the generated value added of about 14 billion EUR in the same year. Three-quarters of the production value is positioned in the downstream segments of wrought semifinished products (rolling, extrusion, drawing) and castings. The total value added at factor cost surged at a remarkable rate of 28% from 2011 to 2018.

The direct employment created by the EU industry rose steadily since 2013, reaching an all-time record in 2018 of 225,000 persons. The highest number of persons employed by the aluminium industry is found in Germany, Italy, and France in absolute figures. As a percentage of the total employment in manufacturing, the aluminium industry has the highest proportion in Greece, Austria, and Hungary.

The investment intensity for NACE 24.42 'Aluminium production' is greater than the average of the EU's metal sectors. In 2018, it achieved the highest level of investments per value added generated than any other metal sector in the EU.

([3]) Nomenclature statistique des activités économiques dans la Communauté européenne

1 Introduction

Europe has embarked on a transition towards a climate-neutral, resource-efficient, circular and competitive economy as envisaged by the European Green Deal ([4]). The pathway to climate neutrality by 2050 sets an intermediate ambitious target of an at least 55% net reduction in greenhouse emissions by 2030, compared to 1990 levels ([5]). Moreover, the transition towards a low-carbon economy must be just and inclusive. Vulnerable workers and citizens, especially those in carbon intensive regions, which are likely to be economically affected by the transition, will be supported by the Just Transition Mechanism ([6]). The new Industrial Strategy for Europe ([7]) aims at addressing Green Deal's priorities, ensuring higher competitiveness for EU producers, and enhancing Europe's strategic autonomy.

Besides, the new Circular Economy Action Plan ([8]) has the ambition to scale up the circular material use rate, reduce the EU's consumption footprint and make a decisive contribution to achieving climate neutrality by 2050. Moreover, the Action Plan on Critical Raw Materials ([9]) points towards the diversified and sustainable supply of critical raw materials and promotes responsible mining practices. At the same time, biodiversity has become a priority of the Union's external action and an integral part of meeting the United Nations Sustainable Development Goals ([10]).

A cross-cutting issue towards the achievement of policy priorities is the sustainability dimension. Raw material suppliers are facing the headwind from growing concerns on sustainability aspects within their supply chain. At the same time, the demand for raw materials is growing worldwide, especially for low-carbon applications. Sustainability is recognised as indispensable for the EU industry to remain competitive ([11]) at a global scale, as well as a key challenge for supply security and the EU's resilience in relation to raw materials ([12]). While the EU is a standard setter in environmental performance and social protection, severe impacts can be outsourced to developing and low governance countries through international trade.

Undoubtedly, given its endless recyclability and light-weighting potential, aluminium is going to be one of the key base metals for the transformational changes required by the policy framework for a resource-efficient, circular and low-carbon society. In fact, aluminium is used in applications in key sectors for unfolding the green transition, such as mobility and construction, but also in low-carbon energy generation technologies. Conversely, aluminium is often a focus in the low-carbon debate as its production entails significant carbon emissions. Meanwhile, the European Commission has included bauxite, the common raw material serving the domestic primary aluminium, in the 2020 list of Critical Raw Material ([13]) given its high supply risk and aluminium's economic importance for the EU manufacturing industry. A considerable share of the bauxite sources to the EU comes from countries having weak governance.

The current report on the sustainability perspective of aluminium production and use is prepared in the framework of the Raw Material Information System (RMIS), the integrated European Union's knowledge platform for non-energy and non-food raw materials. It is the first material-dedicated report in this context with the intention to increase the focus on raw material sustainability. It provides insights into climate change, environmental, social, and circular economy topics for all steps of the aluminium value chain, along with the economic impact of the EU aluminium industry.

In particular, the content is organised as follows:

- ✓ Chapter 2 provides a generic overview of the aluminium value chain, the principal producers and applications.
- ✓ Chapter 3 puts in context the material dimension of the low-carbon transition and the carbon intensity of aluminium production.

([4]) COM(2019) 640 final
([5]) COM(2020) 562 final
([6]) COM(2019) 640 final
([7]) COM(2020) 102 final
([8]) COM(2020) 98 final
([9]) COM(2020) 474 final
([10]) COM(2020) 380 final
([11]) COM(2020) 102 final
([12]) COM(2020) 474 final
([13]) COM(2020) 474 final

- ✓ Chapter 4 pinpoints environmental aspects such as emissions and consumption levels and the main environmental challenges by each value chain stage, the Best Available Techniques covering aluminium production, important Life Cycle Assessment studies, etc…
- ✓ Chapter 5 provides information on social sustainability aspects such as the governance level in countries supplying bauxite to the EU with a focus on the Guinean bauxite sector, occupational health and safety in the aluminium industry, and conflicts triggered worldwide because of activities related to bauxite exploration projects, bauxite mines and alumina/primary aluminium production plants.
- ✓ Chapter 6 discusses circular economy aspects such as the attained recycling rates, the benefits of aluminium recycling in the security of supply and climate change mitigation, the leakage of aluminium scrap to export markets, waste management.
- ✓ Chapter 7 looks at the European aluminium industry's economic dimension concerning the production value and value added, employment and investments.

2 Overview

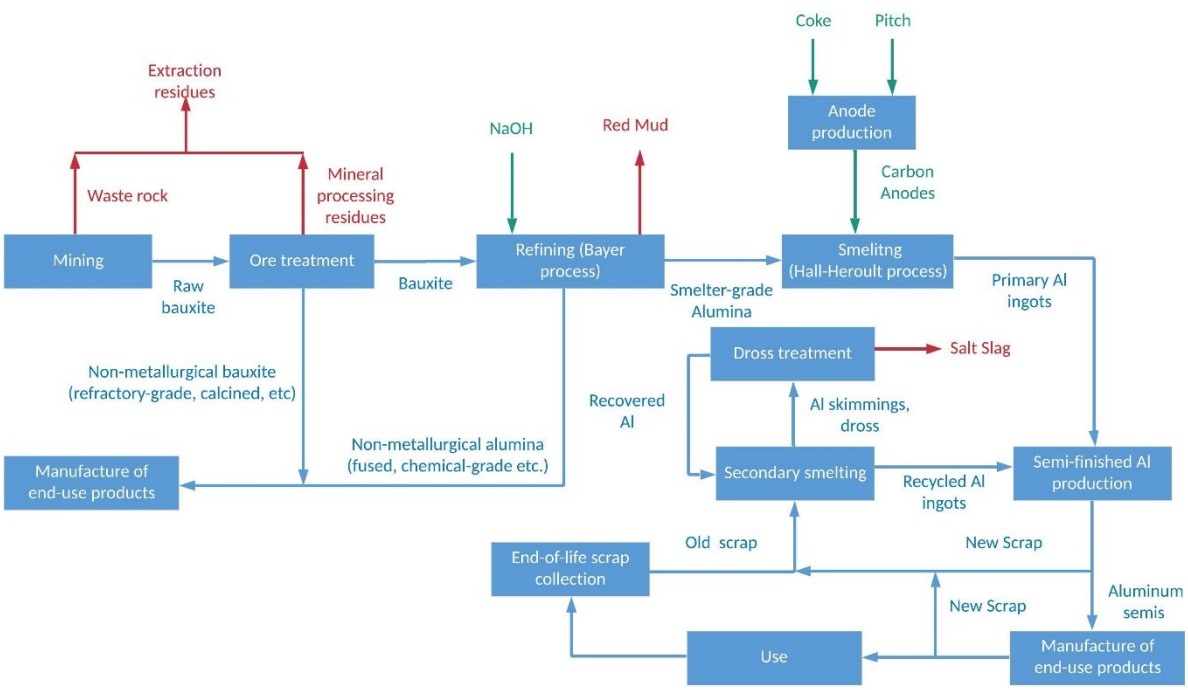
2.1 Definition, main properties, and value chain

Bauxite is the principal aluminium-containing ore for the commercial production of aluminium metal. Bauxite is refined into alumina, which is then smelted into primary aluminium. Bauxite is a heterogeneous ore composed primarily of the aluminium-bearing minerals (aluminium hydroxides or aluminium-oxide-hydroxides) of gibbsite, boehmite and diaspore. It also contains varying quantities of silica, iron oxides and other impurities (Hill and Sehnke, 2006). The average available aluminium oxide content typically ranges from 31% to 52% (IAI, 2009) and the Al content from 16% to 27%. Bauxite is also the main source of supply for gallium as a by-product(Foley *et al.*, 2017). Gallium is included in the list of Critical Raw Materials for the EU ([14]).

Aluminium (chemical symbol Al, atomic number 13) is a lightweight, silver-grey, relatively soft (hardness is 2.75 on the Mohs scale) metal. Its specific weight of 2.7 g/cm^3 is one-third of steel. Aluminium is a good conductor of heat and electricity. Aluminium's superior malleability and the low melting point of 660°C makes it highly workable and versatile. In addition, the ability to form numerous alloys enhances its versatility. Aluminium is alloyed into seven main wrought alloy groups with varying properties. It is also used in several types of cast-alloy grades as well. Another fundamental property is that aluminium has a remarkable strength to weight ratio. By adding elements like zinc and copper to aluminium and through special processing techniques, heat-treatable aluminium alloys can be as strong if not stronger than common steel (Aluminum Association, 2021). Furthermore, aluminium is highly corrosion-resistant as it develops a natural oxide layer, protecting it against corrosion. Finally, aluminium is non-toxic and has good reflective properties. The combination of excellent properties has made aluminium the second most widely used metal in modern society in a vast number of applications and the main non-ferrous metal in terms of production volume.

Figure 1 illustrates the main steps in aluminium production. The aluminium value chain stretches from bauxite mining to alumina, and from primary production through smelting to semi-finished products, end-use products and ultimately to recycling.

Figure 1. Simplified flow chart of aluminium production ([15])

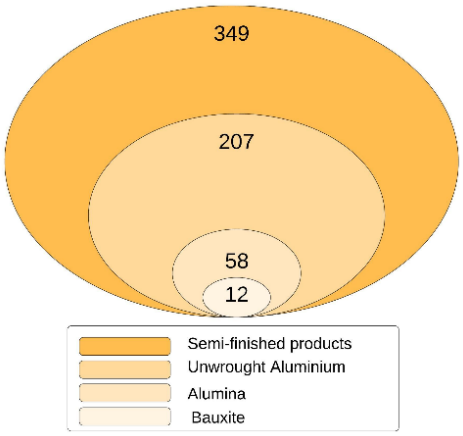


Source: JRC

([14]) COM(2020) 474 final
([15]) The main inputs of auxiliary materials are indicated by green arrows, whereas the main waste streams are reflected by red arrows

The figure below explains the production value of aluminium products in the individual stages of its value chain. The total market value is estimated at more than EUR 620 billion worldwide, from bauxite mining to semi-finished production.

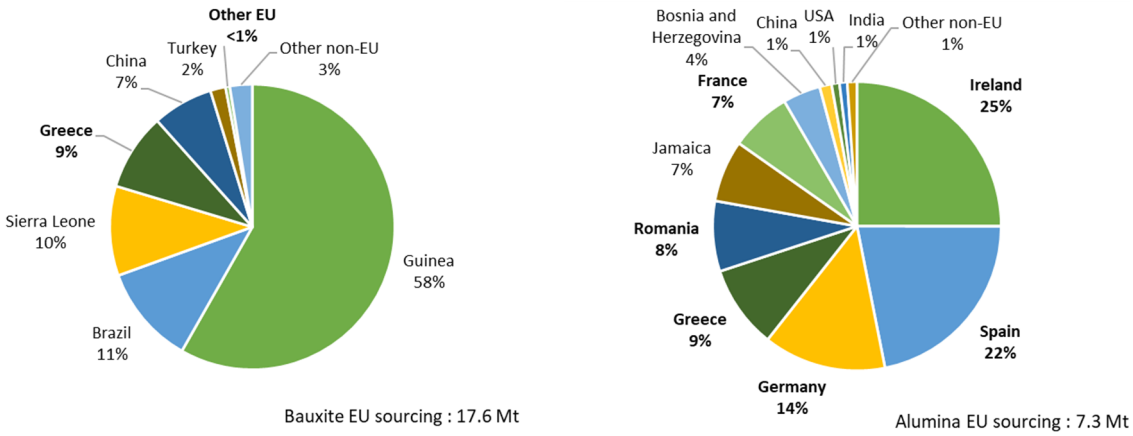
Figure 2. Estimate of market value per stage in the global aluminium value chain in 2018 ([16]), in EUR billions



Source: JRC

Figure 3 demonstrates the countries contributing to the EU supply of bauxite, alumina and unwrought aluminium. Guinea is by far the most significant EU supplier for bauxite, whereas for alumina EU sourcing relies mainly on domestic producers. Unwrought aluminium has a more diversified supply basis, on domestic and foreign producers. As Figure 4 shows, the EU is heavily dependent on bauxite imports (91% in 2018) for its consumption, while for unwrought aluminium the EU is import reliant for about half of it consumption. On the contrary, the EU is a net exporter for alumina.

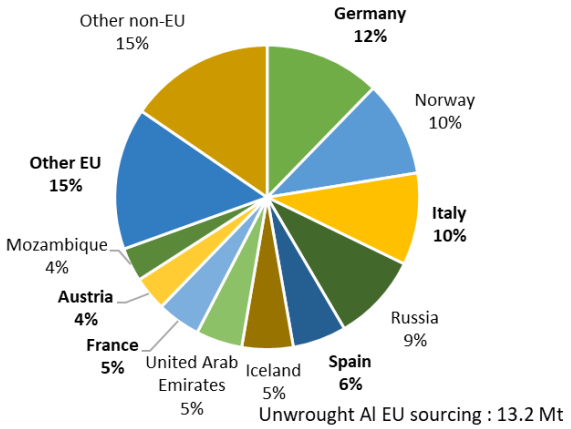
Figure 3. EU sourcing for bauxite (top left), alumina ([17]) (top right) and unwrought aluminium ([18]) (bottom), in 2018



([16]) Data from Eurostat's Prodcom were used to estimate the average unit value of bauxite's production in 2018. Annual prices for smelter-grade alumina were sourced from Focus Economics (https://www.focus-economics.com/commodities/base-metals/alumina), and for specialty alumina from DERA's Price Monitor (https://www.bgr.bund.de/EN/Home/homepage_node_en.html); a split of 90% (smelter-grade)-10% (specialty grades) was assumed for the two alumina broad categories. The annual average LME settlement price in 2018 for standard high grade (99.7%) was employed for unwrought aluminium's unit price (https://www.worldbank.org/en/research/commodity-markets); hence, premiums for unwrought aluminium products of added value (billets, slabs etc) could not be not taken into account in the estimation of the unit value. For aluminium semis, the average unit value was approximated from trade data (global exports statistics providing FOB value) for HS Headings 7604 to 7609 (https://wits.worldbank.org/). The market value was then estimated by multiplying the unit value by the production volume for each product category.

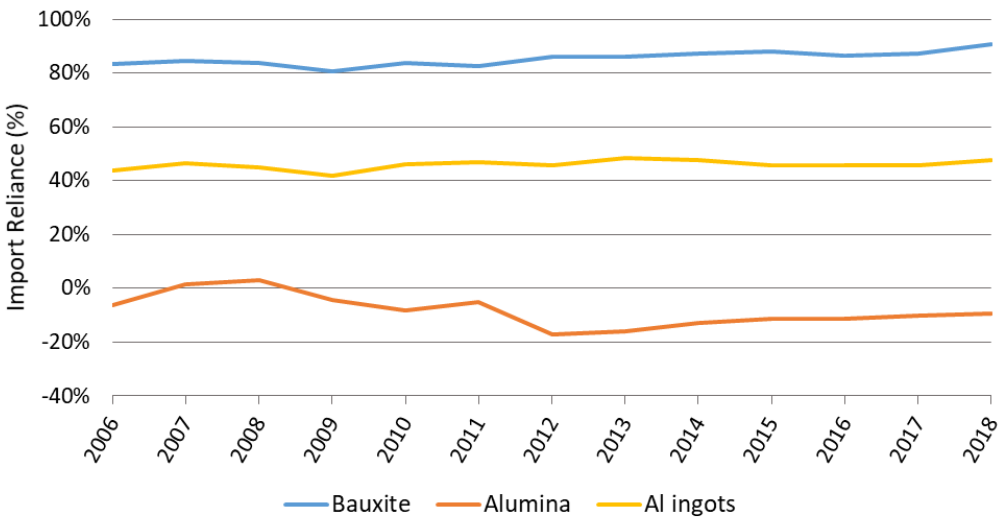
([17]) Trade codes used HS 281820 'Aluminium oxide (excl. Artificial corundum)', HS 281830 'Aluminium hydroxide'. Trade flows of aluminium hydroxide were converted to Al_2O_3 content.

([18]) Unwrought aluminium comprises primary and secondary production. Data for Germany and Spain are partial; the withheld production in Prodcom statistics is included in 'Other EU'.



Source: Data from (Reichl and Schatz, 2020) for bauxite production; (BGS, 2020) for alumina production; (Eurostat Prodcom, 2020) for production of unwrought aluminium; (Eurostat, 2020b) for imports

Figure 4. EU import reliance([19]) for bauxite, alumina, and unwrought aluminium, in 2005-2018



Source: Data from (Reichl and Schatz, 2020) for bauxite production; (BGS, 2020) for alumina production; (Eurostat Prodcom, 2020) for production of unwrought aluminium; (Eurostat, 2020b) for trade flows

2.2 Bauxite resources and mining

According to the United States Geological Survey, bauxite resources worldwide are estimated in the order of 55 to 75 billion tonnes, with 32% located in Africa, 23% in Oceania, 21% in South America and the Caribbean, 18% in Asia, and 6% in the rest of the world. Estimates of known world bauxite reserves are 30 billion tonnes (USGS, 2020). 90% of the world's bauxite reserves are concentrated in tropical and subtropical regions. The world's largest bauxite reserves are located in Guinea (24%) and Australia (20%). Other countries with significant bauxite reserves are Vietnam (12%), Brazil (9%) and Jamaica (7%) (USGS, 2020). In the EU, Greece holds the most significant exploitable bauxite deposits, with an estimated 250 million tonnes of ore reserves as reported by the United Geological Survey (USGS, 2018).Bauxite resources are also located in France, Hungary, Romania and Italy (Minerals4EU, 2015).

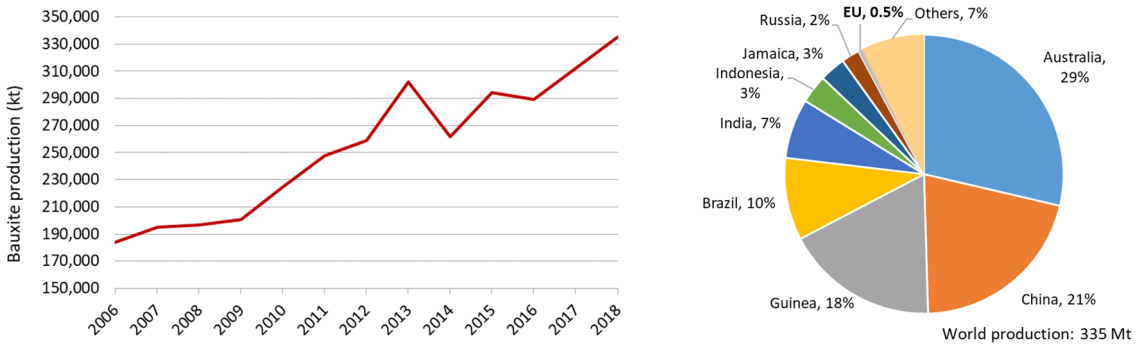
Typical opencast mining techniques are used almost entirely to extract bauxite, and only a minor proportion worldwide is produced from underground mines. According to JRC analysis, 2% of the global bauxite mine capacity is underground, and 3% of mixed type (open-pit and underground); the remaining capacity is exclusively

([19]) Import reliance is calculated as : Net Imports/Apparent Consumption. The apparent consumption is calculated as: Production + Net Imports

operated in open-pit exploitations([20]). The mined ore does not require complex processing because of its relatively high grade (IAI, 2020b).

In the decade 2009-2018, the world's bauxite output grew strongly at a compound annual growth rate of 5.3%. World production of bauxite was about 335 million tonnes in 2018. Australia is the leading producing country (29% of the total) followed by China (21%) and Guinea (18%). The bauxite output in the EU represents a minor share of 0.5% of the global at around 1.7 million tonnes in 2018. Greece produced 95% of the EU total; France, Croatia and Hungary accounted for 5%. (Reichl and Schatz, 2020).

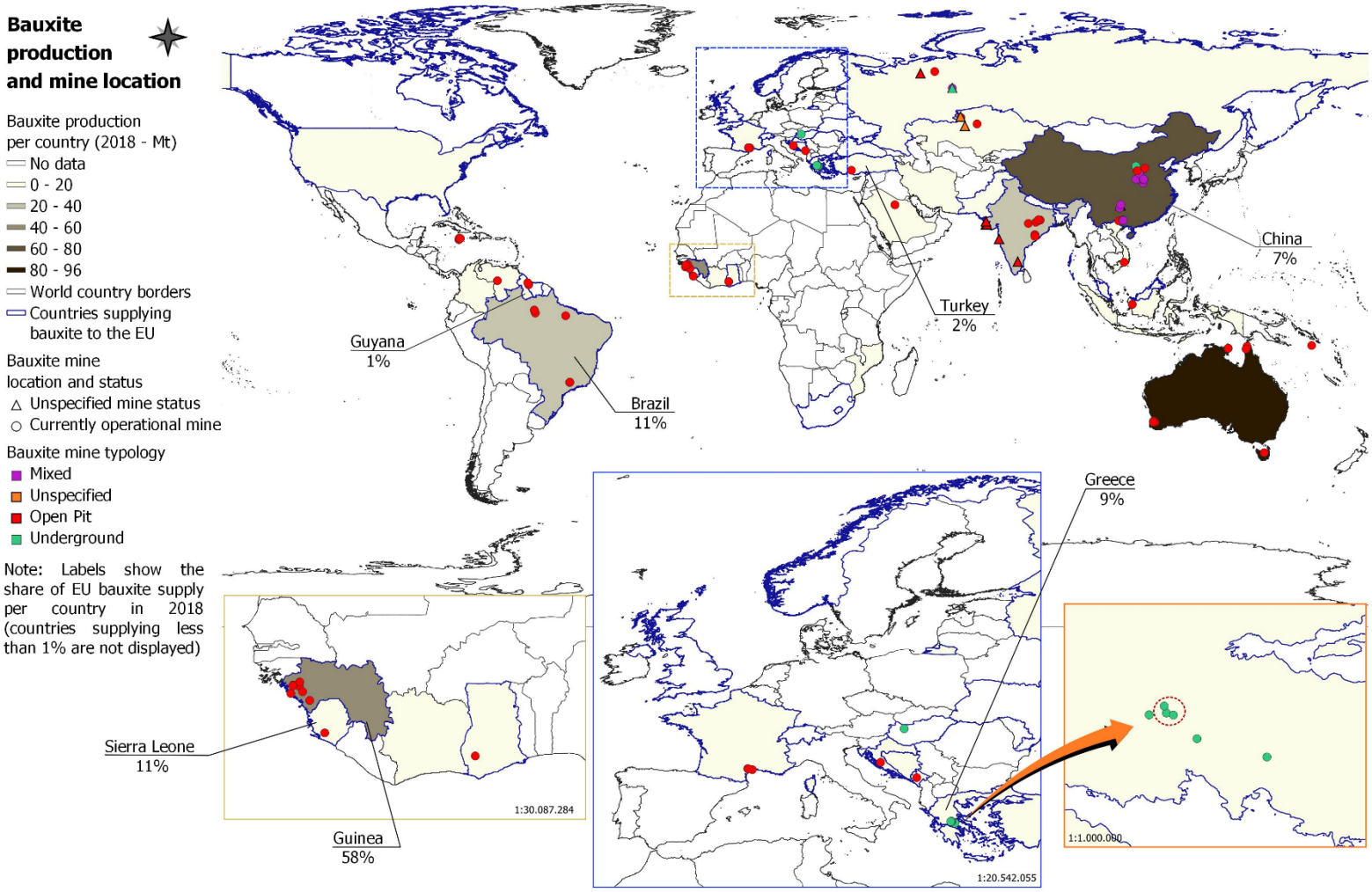
Figure 5. Evolution of bauxite's world production (left), and breakdown by countries in 2018 (right)



Source: Data from (Reichl and Schatz, 2020).

([20]) Annex 1 describes the applied methodology and data sources for developing the bauxite mine datasets.

Figure 6. Bauxite mine location worldwide



Source: JRC elaboration based on (Reichl and Schatz, 2020) for bauxite production; (S&P Global, 2020) and several other sources for mines' location and operating status.

2.3 Aluminium production

There are two routes for aluminium metal production: primary aluminium production from bauxite ore through a series of long-established processes, and secondary production from aluminium scrap.

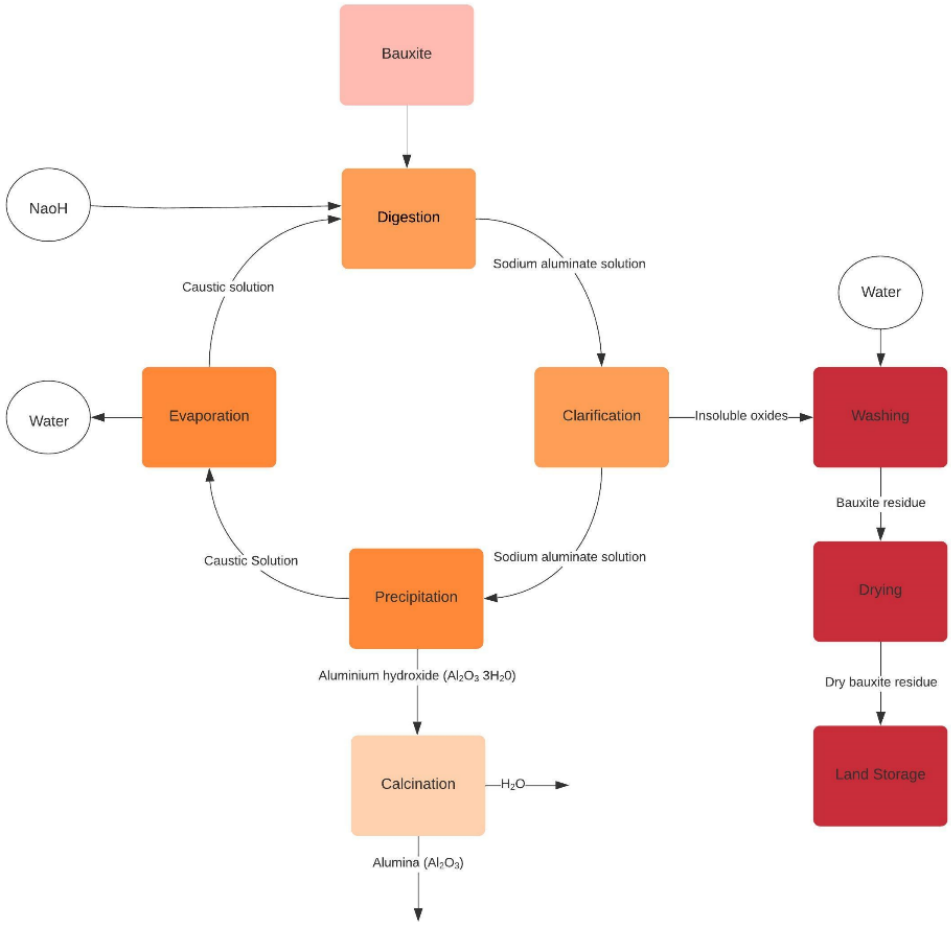
2.3.1 Primary aluminium

Primary aluminium is produced from aluminium oxide (alumina) in a two-stage process starting from bauxite.

2.3.1.1 Alumina refining

In the first stage, alumina (Al_2O_3) is extracted from bauxite through a progressive series of steps in the so-called Bayer process. Bauxite ore is initially ground and dissolved in a hot solution of caustic soda (NaOH) and lime under pressure, within a digester at temperatures of between 140°C and 280°C depending on the type of ore. Under these conditions, bauxite's aluminium-bearing minerals dissolve in the alkaline solution to form a sodium aluminate supersaturated solution. The sodium aluminate solution is then thickened and filtered in a clarification step to separate the iron oxides and other insoluble bauxite components via sedimentation (bauxite residue, also called 'red mud'). Aluminium hydroxide trihydrate (also called aluminium hydrate) is then precipitated by cooling the saturated liquor and adding crystal seeds. Next, the precipitate is filtered and washed to recover the caustic solution. Finally, aluminium hydroxide goes through a calcination process at about 1,100°C to drive off free and chemically combined water, leaving pure alumina, a fine-grained white powder (IAI, 2020i)(European Aluminium, 2013). Approximately 90% of the global alumina supply is used in aluminium production, while non-metallurgical applications in the refractories and chemical industry use the rest (speciality alumina grades) (IAI, 2020i).

Figure 7. Simplified flow chart of the Bayer process

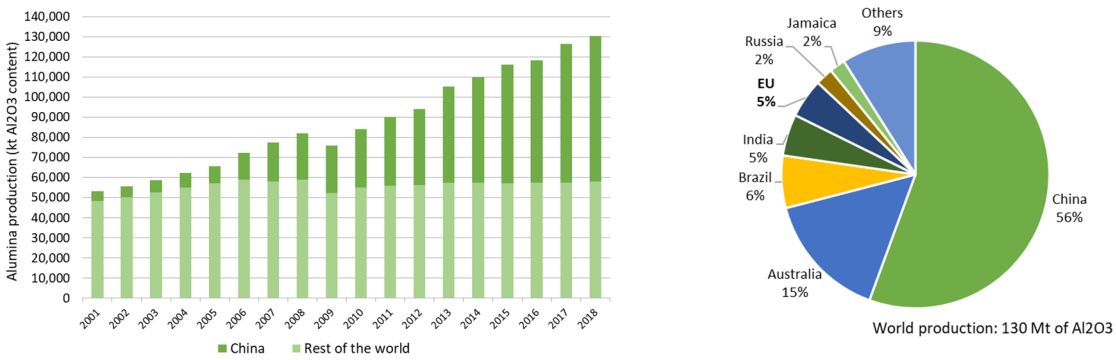


Source: JRC

Alumina's world production has increased considerably during the past decade 2009-2018 at a compound annual growth rate of 5.6% and reached 130 Mt in 2018. The driver has been the enormous surge in Chinese production, which has grown at a CAGR of 11,8% over 2009-2018. From a global share of just 9% in 2001, China has come to produce a share of 56% of the worldwide output in 2018. The massive build-up of China's alumina refining capacity was driven by the vast expansion of China's primary production (Aluminum Association et al., 2018). Other significant producers are Australia (15%) and Brazil (6%).

EU's domestic alumina production amounted to about 6.1 Mt in 2018, holding a share of 5% of the world total. Ireland (30%), Spain (26%), and Germany (16%) are the leading producers among six EU producing countries (BGS, 2020).

Figure 8. Evolution of alumina's world production (left), and breakdown per countries in 2018 (right)



Source: Data from (BGS, 2020).

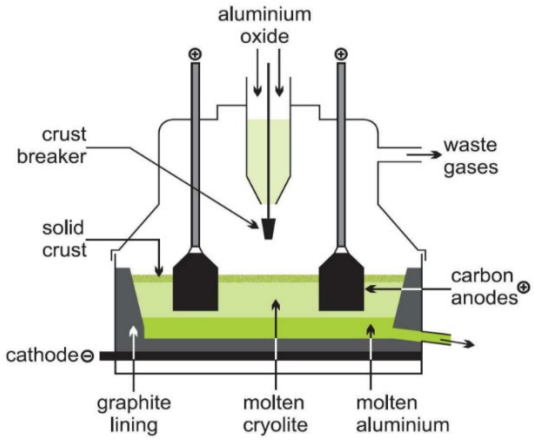
2.3.1.2 Aluminium smelting

The second stage comprises the electrolytic reduction of aluminium oxide to aluminium. The electrolytic process, known as the Hall-Héroult process, is carried out in smelting plants. This is the most energy-intensive stage in the aluminium production chain requiring massive amounts of electricity. The Hall-Héroult process is a fused-salt electrolysis that comprises aluminium oxide's breakdown into aluminium and oxygen using direct current.

The electrolytic cells (also known as 'pots') involve a carbon cathode, insulated by refractory bricks inside a rectangular steel shell, and suspended consumable carbon anodes. The floor of the steel box is lined with graphite (carbon) which acts as the cathode. In the pot room, the cells are connected in series to form an electrical reduction line (potline). During operation, alumina is dissolved into a molten aluminium fluoride (cryolite) bath that lowers the mixture's melting point to a temperature of approximately 960 °C. Alumina is added to the cells to maintain an alumina content of 2–6 % in the molten bath. The boxes are designed so that cryolite solidifies in a thin layer on the surface of the electrolyte. A direct current is passed from the carbon anodes through the bath and a layer of metal to the cathode and then, by a set of current conductors known as 'busbars', to the next cell (Cusano *et al.*, 2017)(CIES, 2016). Aluminium is denser than the molten electrolyte and is deposited at the bottom of the cell, from where it is transferred to the casthouse. At the anodes, the anodic reaction takes place, i.e. conversion of oxygen to carbon dioxide by reaction with anodes' carbon. Depending on the ore grade, it takes 4-6 tonnes of bauxite to refine approximately 2 tonnes of alumina, which in turn are smelted to make 1 tonne of primary aluminium metal([21]).

([21]) The conversion ratio in 2018 worldwide was 5.23 tonnes bauxite: 2 tonnes alumina: 1 tonne primary aluminium in accordance with production data. The stoichiometric minimum requirement in smelting is 1,889 kg Al_2O_3 per 1,000 kg of primary aluminium (IAI, 2017).

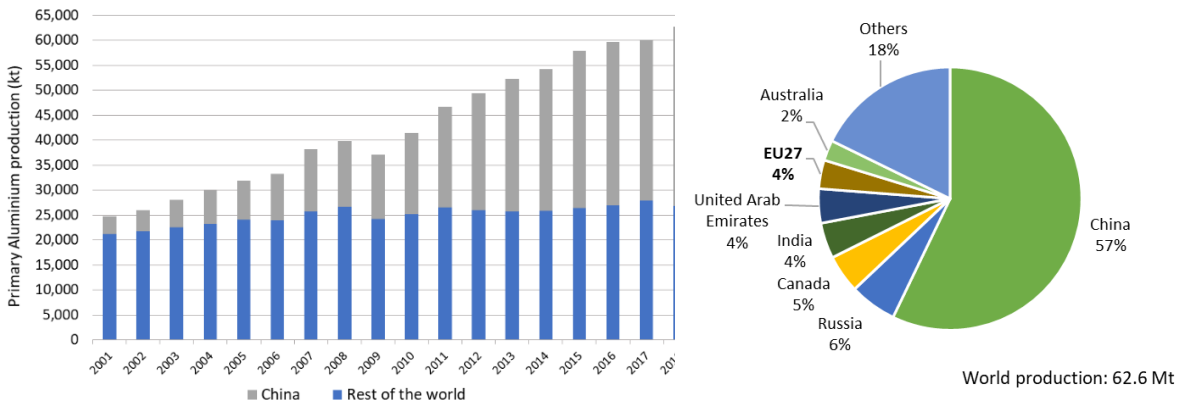
Figure 9. An electrolytic cell in primary aluminium production



Source: (CIES, 2016).

Primary aluminium production worldwide amounted to 62.6 Mt in 2018. China dominates the world output by the overwhelming share of 57%, followed by Russia (6%), Canada (5%) and India (4%) (BGS, 2020). China's production of primary aluminium has been multiplied by ten since 2001 (Figure 10). EU countries represent approximately 4% of the global primary aluminium output (2.2 Mt in 2018). Germany (24%), France (17%) and Spain (16%) are the leading Member States among nine producing EU countries.

Figure 10. Evolution of primary aluminium's world production (left), and breakdown per countries in 2018 (right)



Source: Data from (BGS, 2020).

2.3.2 Secondary aluminium

Recycling of aluminium scrap involves the collection, sorting, pre-treatment, melting and ingot casting. Secondary aluminium production is characterized by the diversity of old scrap types available, i.e. a high variety of alloys, size, type and degree of contamination by paints, ink or plastics, which correspondingly determines the necessary pre-treatment technique (e.g. mechanical separation) and the melting process to be applied (e.g., rotary furnace with salt flux) (European Aluminium, 2016).

Box 1. The aluminium recycling industry and its raw materials

Recycled (or secondary) aluminium is produced by melting old and new aluminium-bearing scrap:

- **New or process scrap**: generated from the fabrication of semi-finished aluminium and the manufacturing of finished products, such as extrusion discards, sheet edge trimmings, turnings, millings etc.
- **Old or post-consumer scrap**: post-consumer scrap recovered from end-of-life sources, such as used beverage cans, engine blocks, aluminium window systems, electrical conductor cables, etc.

The aluminium recycling industry can be grouped into two different segments in relation to the downstream use of products and the aluminium alloy family that is produced.

- **Remelters** produce aluminium wrought alloys from old and new scrap, mostly in the form of extrusion billets and rolling ingots. Their products are inputs for the manufacture of extrusions and rolled products. In general, aluminium scrap input is comprised of wrought alloys because of the narrow tolerances of the composition of produced wrought alloys. The production process demands segregated aluminium scrap, whereas primary aluminium may also be added in the charge to dilute the melt. The selection of an optimised mix of types of scrap to be charged in the melting furnace against the alloy types that will be produced is vital to reduce raw material costs in the secondary production of aluminium.

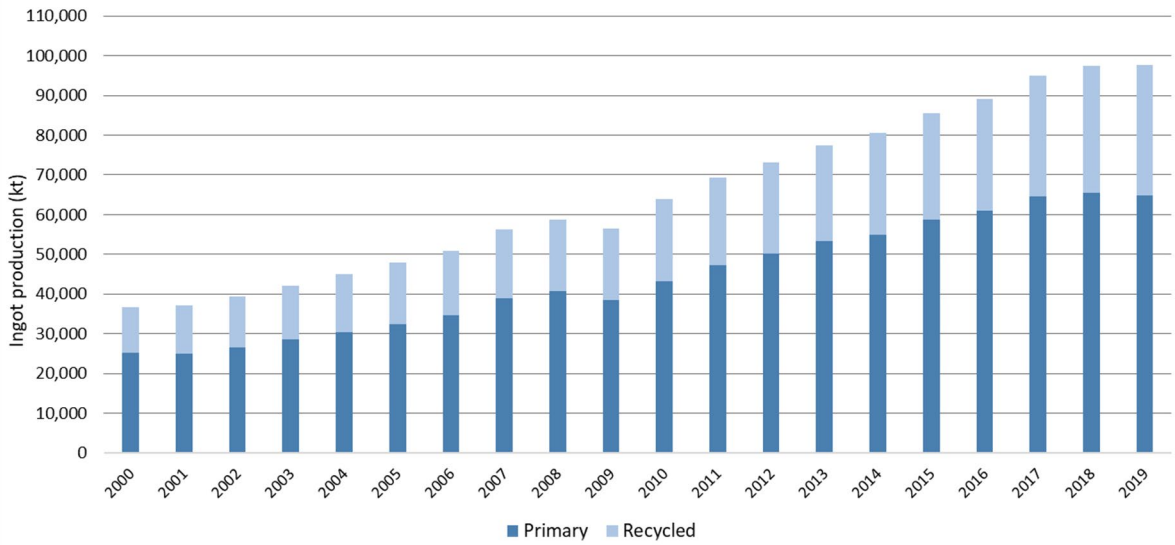
Remelters are often part of the downstream organisation and even sometimes integrated. Integrated casthouses in plants producing semi-finished aluminium (e.g., rolling and extrusion plants) perform internal remelting of mainly clean process (new) scrap to produce ingots of wrought alloys for in-house consumption.

- **Refiners** produce secondary aluminium casting alloys (or 'foundry alloys') using diverse types of old scarp, as casting alloys have a much higher tolerance of impurities than wrought alloys. Process scrap from the automotive industry is also a considerable raw material. Their products (ingots and liquid metal) are the input to casting plants (mainly die-casters) to produce aluminium castings, predominantly destined for the automotive industry. Refiners also produce aluminium deoxidisers for the steel industry.

Source: (European Aluminium, 2018b) (Bertram et al., 2017) (Saveyn et al., 2014)

The recycled aluminium ingot production is estimated at approximately 30.7 Mt in 2018, from a feedstock consisting of about 61% old scrap and 39% new scrap. China accounts for one-third (33%) of the global output (IAI, 2020d). Recycled aluminium ingots (old and new scrap) represent about one-third (31-34% during 2000-2019) of global aluminium production (Figure 11), covering the gap between the growing metal demand and primary metal supply.

Figure 11. Evolution of production for unwrought aluminium ingots globally ([22])



Source: Background data from (IAI, 2020d).

2.4 Semi-finished aluminium and its demand

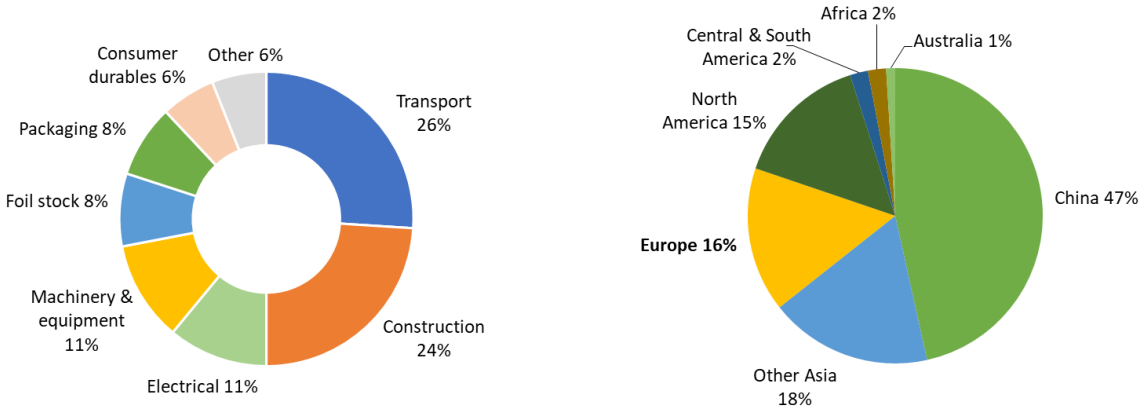
Semi-finished aluminium products (or 'semis') are defined as products that have undergone some processing and are supplied for further mechanical working (e.g., forming, machining, joining) into a finished form before their use. Wrought aluminium products (or 'mill' products) and aluminium castings belong to the 'semis' broad group. The input material for wrought products is unwrought aluminium metal (primary or secondary) that is mechanically hot or cold worked by rolling, extruding, drawing or forging into multiple forms. Wrought aluminium products include flat-rolled products, extruded products such as bars, rods and profiles, as well as aluminium wire, tubes and pipes. Aluminium castings are produced in foundries by casting processes, including die-casting, sand or permanent mould casting, and investment casting. The input material is unwrought aluminium (casting alloys) (Aluminum Association, 2009) (European Aluminium, 2018b).

The global output of semi-finished aluminium products is estimated at 95.1 Mt in 2018. China accounts for about 48% of the global total, while Europe and North America for 14% and 12%, respectively. Going further, the volume of aluminium that is finally consumed in end-use products in 2018 was 82.4 Mt (IAI, 2020d).

Figure 12 illustrates the distribution of aluminium uses across different sectors and world regions. It is notable that half of the aluminium demand worldwide is destined for the transportation and construction sector. In Europe, the transport & automotive, construction and packaging market applications account for more than 80% of aluminium demand (Figure 13).

([22]) Aluminium ingot supply is not available via statistical data. Material flows are calculated by a mass balance approach based on semis shipments, primary production, utilisation rates and trade (Bertram et al., 2017).

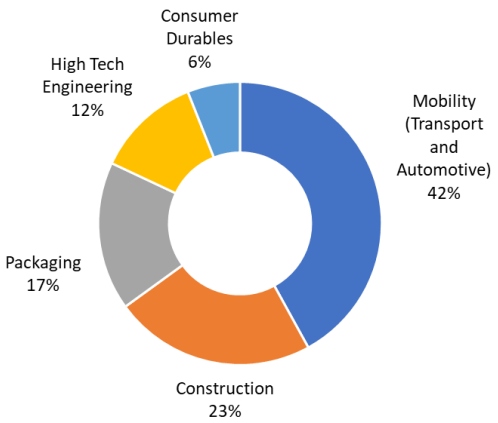
Figure 12. Aluminium market applications worldwide (left) and consumption by world region (right), in 2019



Global consumption ~ 90 Mt

Source: Hydro and CRU data in (Hydro, 2020).

Figure 13. Aluminium market applications in Europe in 2017



Source: (European Aluminium, 2018a).

3 Climate Change

3.1.1 Greenhouse gas emissions of production

3.1.1.1 Overview

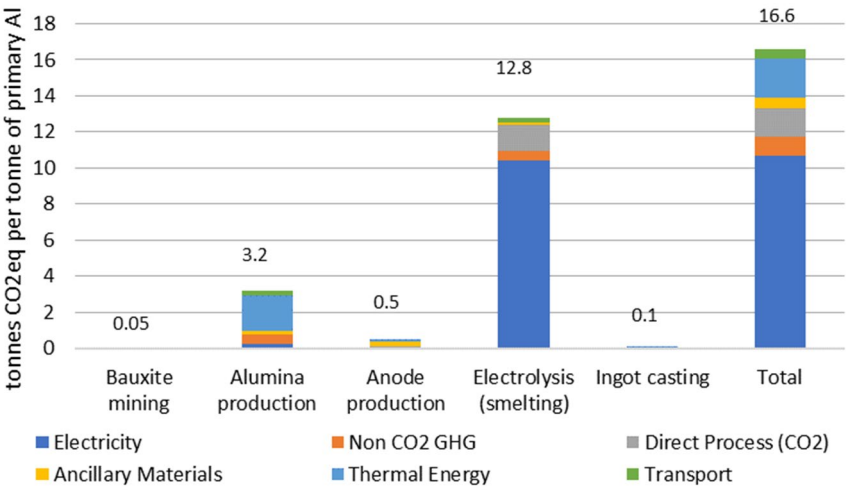
Greenhouse gases (GHG) emissions are the main environmental concern for aluminium metal production (OECD, 2015). The EC Product Environmental Footprint (PEF) pilot phase for metal sheets made of aluminium also identified the climate impact as the most significant environmental impact (European Commission, 2019b) (Eurometaux, 2019).

Electricity generation, which is used as an input into the electrolysis process of primary aluminium production, is the most emission-intensive source of GHG in aluminium production. Aluminium smelting requires large amounts of electricity, typically around 14-15 MWh per tonne of metal produced (see Figure 22). According to the data published by the International Aluminium Institute, indirect emissions from electricity generation consumed during the smelting process account for 61% of the total GHG emissions in the aluminium sector worldwide (mining to semi-finished products).

The rest (39%) of GHG emissions results from the industrial production process itself (including mining, refining, smelting, semis production, and recycling) (IAI, 2020c). The direct GHG emissions are generated either by process-specific reactions, i.e. from anode consumption, and Perfluorocarbon gases (PFCs) emissions from the electrolytic process in primary production, or by the combustion of fuels, e.g., in the boilers for alumina refining, remelting and heating furnaces. The direct (process) emissions comprise predominantly CO_2 but also other gases with high Global Warming Potential (GWP), i.e. tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6), which are released intermittently.

Figure 14 shows how the global average carbon footprint is determined as CO_2eq per tonne of primary aluminium production, considering bauxite mining from the ore, alumina production, anode production for smelting, and the ingot casting process.

Figure 14. Greenhouse gas (GHG) emissions by unit process and process type in primary aluminium production([23]) worldwide, in 2018



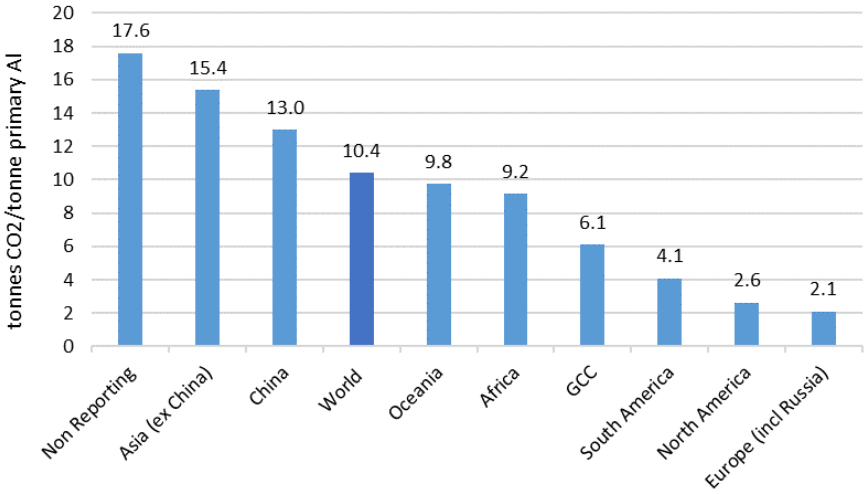
Source: (IAI, 2020c).

At the global level, indirect emissions from electricity production required to power electrolytic smelting are about 11 kg CO_2eq/kg primary Al, accounting for 81% of the total smelting process' GHG emissions and 63% of primary aluminium's carbon footprint (IAI, 2020c). Thus, indirect GHG emissions associated with electricity use for primary aluminium production depend on the local electricity provider's energy mix and vary

([23]) Primary aluminium production worldwide in 2018 64 Mt, and associated global GHG emissions 1,052 Mt. World coverage, the 2018 update is based on 2015 LCI data.

considerably across regions as data in Figure 15 show (see also Figure 19). Other significant impacts in aluminium smelting are the direct emissions from the anode consumption during electrolysis.

Figure 15. Carbon footprint of electricity for aluminium electrolysis by world regions in 2018([24])



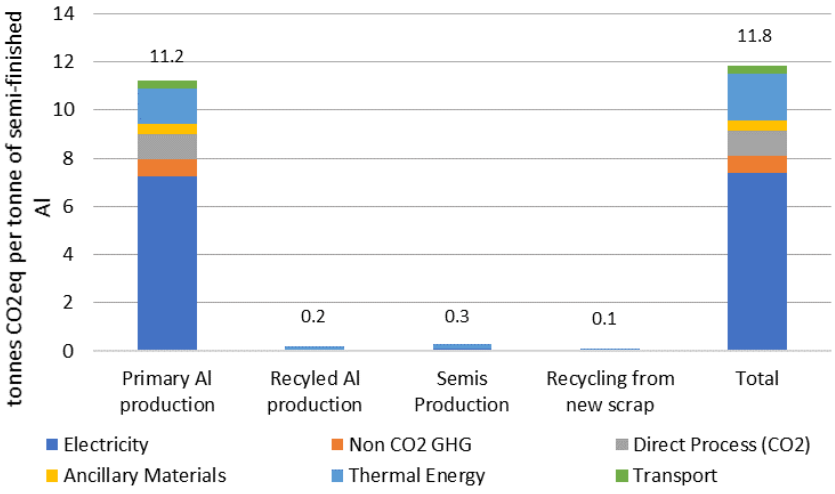
Source: (IAI, 2020c).

The next more GHG-intensive stage of the aluminium value chain is the alumina production process from bauxite (Bayer process) that accounts for about 19% of the total GHG emissions to produce one tonne of primary aluminium (Figure 14). About 60% of GHG emissions associated with alumina production are related to alumina calcination's thermal energy, thus the magnitude of GHG emissions in alumina production is mainly a function of the thermal energy fuel mix. Conversely, bauxite mining is responsible for a minimal amount of GHG emissions compared to refining of bauxite to alumna and electrolytic reduction of alumina.

GHG emitted at other stages of the aluminium value chain are much lower (see Figure 16). It is notable that the secondary route of aluminium production, i.e. from recycling, reduces energy consumption by 95%; savings of CO_2 emissions are up to 98% (Material Economics, 2018). This route involves the collection, sorting, pre-treatment, melting and casting. No GHGs are produced in the recycling of aluminium other than from the fuels used for remelting, resulting in more than 50 times lower GHG emissions compared to the primary route. Figure 16 below demonstrates the overall carbon footprint of the aluminium industry expressed in terms of production of semi-finished aluminium.

([24]) Europe: EU27 countries, Bosnia-Herzegovina, Iceland, Montenegro, Norway, Russian Federation, Serbia, Switzerland, Ukraine, United Kingdom.

Figure 16. Greenhouse gas (GHG) emissions (as CO_2 equivalent per tonne of semi-finished production) in the aluminium sector worldwide per industrial segment, in 2018 ([25])

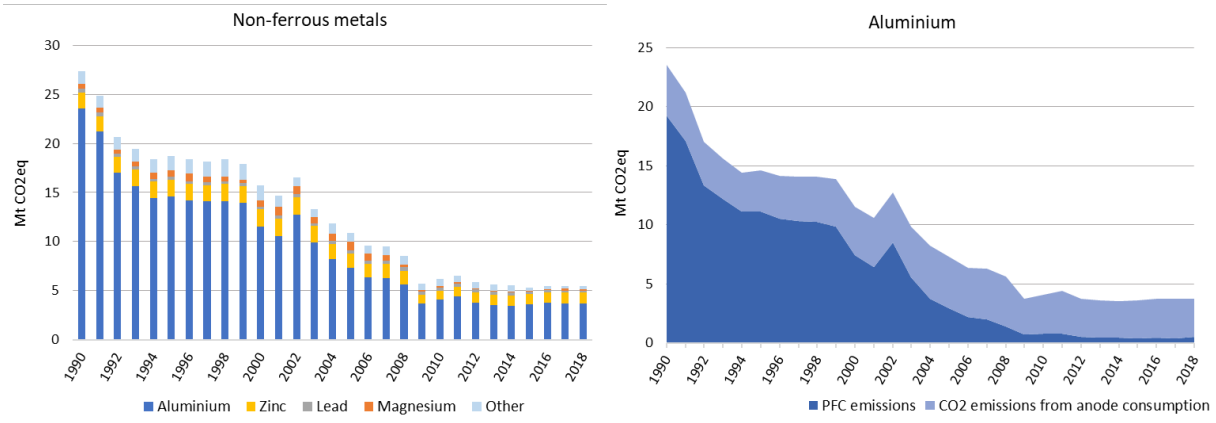


Source: (IAI, 2020c).

3.1.1.2 Focus in the EU

The European Environmental Agency estimated that the aluminium sector accounted in 2018 for 1.1% of the EU's industrial emissions (EEA, 2020). Aluminium production covers the largest part of greenhouse gas emissions of the non-ferrous metal's output in the EU (Figure 17). The absolute direct (process) GHG emissions from primary aluminium production have declined significantly since 1990, as data from two separate sources reveal in Figure 17 and Figure 18.

Figure 17. Evolution of direct (process) GHG emissions([26]) in the EU for non-ferrous metals (left) and breakdown per gas for aluminium (right), 1990-2018

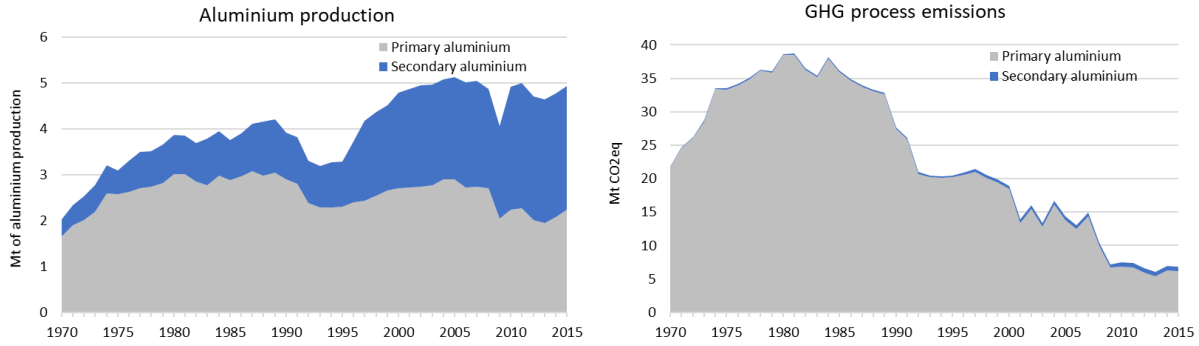


Source: JRC elaboration based on (EEA, 2020).

([25]) All processes from mine (primary route) and end of life product collection (recycling route) to semis fabrication including ancillary processes, transport and electricity production. Estimated semis production worldwide in 2018 95 Mt, and associated global GHG emissions 1,127 Mt. The 2018 update is based on 2015 LCI data.

([26]) As reported by EU member states to the UNFCCC and the EU's GHG monitoring mechanism (IPCC sector: Aluminium 2.C.3, Magnesium 2.C,4, Lead 2.C.5, Zinc 2.C.6, Other metals 2.C.7)

Figure 18. Evolution of aluminium production (left), and cumulative GHG direct (process) emissions ([27]) (right) in the EU, 1970-2015



Source: JRC elaboration based on (EDGAR, 2020).

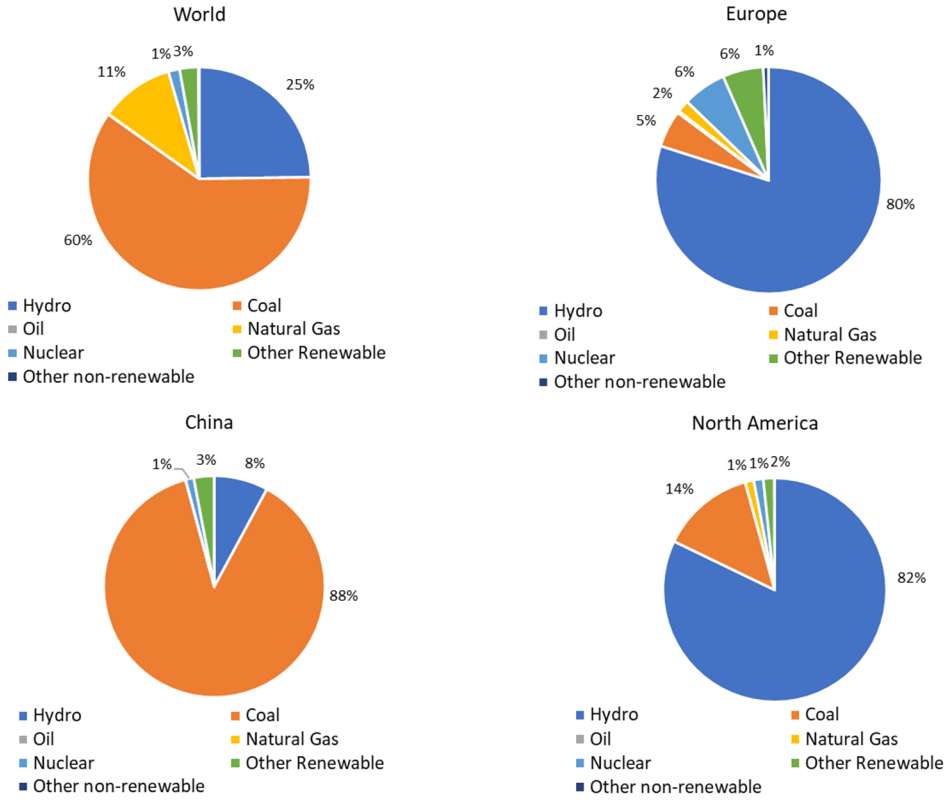
The EU aluminium industry's absolute emissions have been reduced from 23.5 million tonnes of CO_2eq in 1990 to 3.7 million tonnes in 2018, a fall of 84% (Figure 18). The decrease in GHG emissions' total amount can be explained partly by the decline of primary aluminium production in the EU; between 1990 and 2018, primary aluminium output fell by 14% (BGS, 2020). Simultaneously, secondary aluminium production has taken over, which is much less GHG emissions intense (see Figure 18). Another factor contributing to the drop in emissions is the massive reduction of emissions per unit of production achieved by the European ([28]) primary aluminium producers. The reduction in direct GHG emissions per tonne of primary production was 20% between 2010-2015, and 55% in total between 1990 and 2015, i.e. from 15 t CO_2eq/t in 1990 to 8.5 t CO_2eq/t in 2010, and further to 6.7 t CO_2eq/t as a European average in 2015 ([29]). It is noteworthy that the global average carbon intensity of primary aluminium production was 18 t CO_2eq/t of aluminium in 2015 (European Aluminium, 2019d)(European Aluminium, 2018b). For comparison, this is more than seven times the emissions associated with producing one tonne of primary steel (Material Economics, 2018)(OECD, 2019).

The outstanding decrease is due to the sharp decline of carbon dioxide equivalent emissions from Perfluorocarbon gases (PFCs) that fell by 97% over the same period (see Figure 17). That was achieved from the implementation of advanced process management (closely control cell voltages and the alumina content in the cell) to avoid anode effects and limit the duration of any that do occur ([30]) (Cusano *et al.*, 2017). Concerning CO_2 emissions from anode consumption, a decrease of 26% is recorded between 1990 and 2018 in the EU, a rate which is higher than the decline of the primary aluminium output over 1990-2018 (14%).

The source of electricity has a major impact on primary aluminium's carbon footprint. Aluminium smelting plants are usually placed in locations different from the mine sites; logistics and access to electricity at favourable terms are the main factors determining the plant's position. According to the International Aluminium Institute, 93% of European production([31]) used non-fossil sources of electricity in 2019 (Figure 19). Hydropower is the primary source of electricity for aluminium smelters in Europe. Coal and oil are progressively phased out from the energy sources to power European smelters (Figure 20). Contrarywise in China, which accounts for more than half of global supply, electricity used by aluminium smelters is typically generated by coal-fired plants (88%). Globally, the majority (60%) of produced aluminium used coal-fired electricity in 2019.

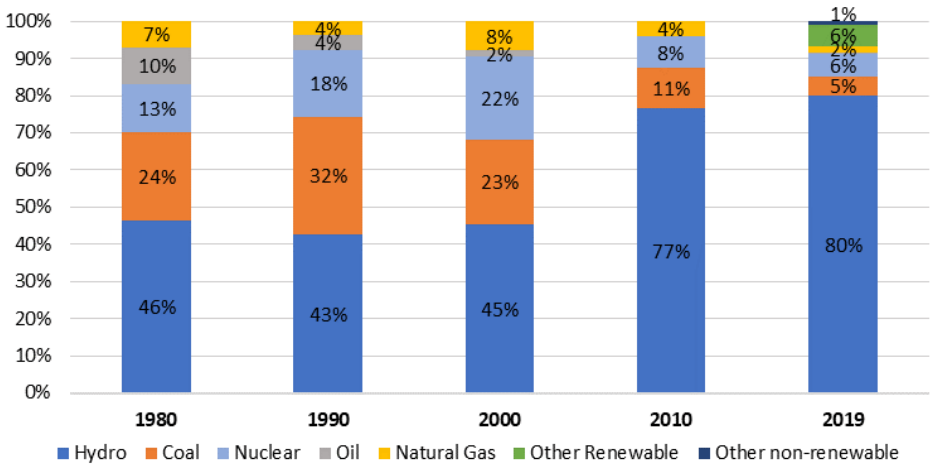
([27]) The Emissions Database for Global Atmospheric Research (EDGAR) provides independent estimates of the global anthropogenic emissions and emission trends, based on publicly available statistics.
([28]) EU+UK+EFTA.
([29]) Cradle-to-gate, including emissions from bauxite mining and alumina refining.
([30]) The PFCs tetrafluoromethane (CF_4) and hexafluoroethane ($C2F_6$) are formed during the so-called 'anode effects', that occurs when the alumina content of the electrolyte falls below 1–2 %. During an anode effect, instead of decomposing alumina, the cryolite bath is decomposed into metal and fluoride ions that react with the anode carbon and form gaseous PFC emissions.
([31]) Europe: EU27 countries plus Bosnia-Herzegovina, Iceland, Montenegro, Norway, Russian Federation, Serbia, Switzerland, Ukraine, United Kingdom.

Figure 19. Primary aluminium smelting power consumption per energy source ([32]) and selected world regions in 2019



Source: Data from (IAI, 2020h).

Figure 20. Evolution of energy mix used in primary aluminium smelting in Europe



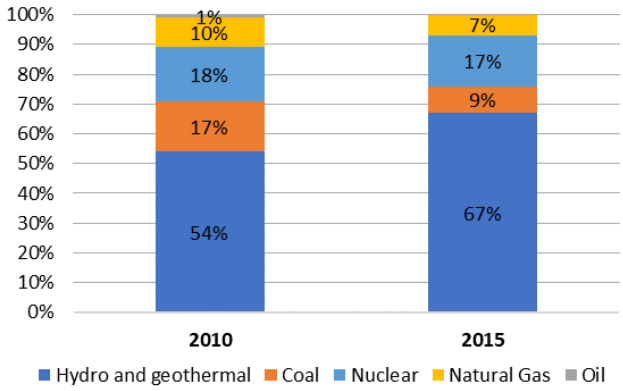
Source: Data from (IAI, 2020h).

Consolidated data published by the European Aluminium for the energy sources used by smelters in the EU+UK+EFTA countries, also show that the energy mix for primary aluminium production in Europe in 2015 is having much more hydro and geothermal electricity in comparison to 2010 (67% in 2015 vs 54% in 2010) and less coal (9% in 2015 vs 17% in 2010). This is explained by the increase of the production share of EFTA

([32]) Energy sources with a proportion of less than 1% are not displayed. See note ([24]) for countries included in 'Europe'.

countries (Norway and Iceland) from 40% to 50% between 2010 and 2015, which have a high proportion of renewable energy in their energy mix, and smelter closures in the EU.

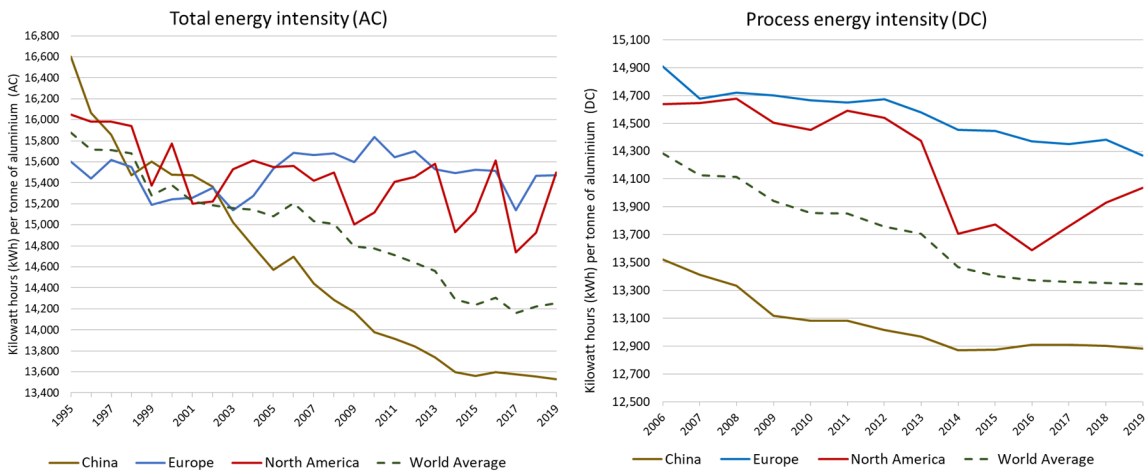
Figure 21. Evolution of energy mix used in primary aluminium smelting in EU+UK+EFTA([33]) by type of generation



Source: (European Aluminium, 2013)(European Aluminium, 2018b).

Data published by the International Aluminium Institute show that the energy intensive process (DC) in European smelters has improved by about 4% from 2006 to 2019, and the world's average rate of improvement has been about 6% in the same period (Figure 22). Moreover, data reveal that Chinese smelters have a lower total energy consumption (AC) compared to the world average since 2005, driven by far more efficient electrolysis process on average (DC). Chinese smelters' lower process energy intensity reflects the installation of new capacity with the best available technology over the last years, in combination with the closure of older, less efficient facilities (IAI, 2017). On the other hand, the total energy intensity in primary aluminium smelting in Europe has remained relatively steady in the last years and, higher than China's and world's average (Figure 22).

Figure 22. Energy intensity (AC and DC) in primary aluminium smelting ([34]),([35]) per specific world regions



([33]) Consolidated data referring to 2015 collected from industries, which cover about 90% of the European production, indicated an electricity grid mix composed of 71% hydro energy, 12% nuclear, 10% coal and 6% natural gas. The national electricity grid by type of generation was used to represent the remainder of European production.

([34]) See note ([24]) for countries included in 'Europe'.

([35]) The energy intensity in primary aluminium smelting is reported as AC and DC power used for electrolysis by the Hall-Héroult process per tonne of aluminium production. The AC value refers to the power consumed by facilities for the smelting process including rectification from AC to DC, and the electrical energy used by associated smelter auxiliaries (e.g., pollution control equipment) up to the point where the liquid aluminium is tapped from the pots. It excludes power used in casting and carbon plants. The DC value is a process efficiency metric, measuring the energy intensity of the electrolytic process as the consumption of DC power after rectification per tonne of liquid aluminium tapped from the pots. Data are based on industry reports; sources outside the industry or estimates are used by the International Aluminium Institute (IAI) for China.

Source: Background data from (IAI, 2020g).

However, the high-carbon footprint of primary aluminium produced in China is remarkable. In 2019, coal-fired plants generated 88% of Chinese smelters' power consumption compared to 8% in Europe([36]) (see Figure 19). Producing one tonne of aluminium in China generates about 20 t of CO_2eq. That compares to 6.7 t of CO_2eq per tonne of aluminium produced in EU+UK+EFTA ([37]), i.e. European producers emit overall one-third of the GHG emitted by Chinese producers (European Aluminium, 2018a)(European Aluminium, 2019d).

3.1.1.3 EU regulatory instruments

The EU Emissions Trading System (EU ETS), as well as the potential introduction of a Carbon Border Adjustment Measure (CBAM), are instruments for reducing industrial greenhouse gas emissions from the aluminium industry.

Box 2. The EU Emissions Trading System

The EU Emissions Trading System (EU ETS) is a cornerstone of the EU's policy to combat climate change. Set up in 2005, the EU ETS is the world's first international emissions trading system and remains the biggest one. The EU ETS has proven to be an effective tool in driving emissions reductions cost-effectively. Installations covered by the ETS reduced emissions by about 35% between 2005 and 2019. The EU ETS works on the 'cap and trade' principle. A cap is set on the total amount of certain greenhouse gases that the installations covered by the system can emit. The cap is reduced over time so that total emissions fall. Within the cap, installations buy or receive emissions allowances, which they can trade with one another as needed.

The EU ETS covers the aluminium sector since 2013 for the following segments and gases:

— Production of primary aluminium: Carbon dioxide and perfluorocarbons (PFCs);

— Production of secondary aluminium, where combustion units with a total rated thermal input exceeding 20 MW are operated: Carbon dioxide;

— Production of aluminium castings, where combustion units with a total rated thermal input (including fuels used as reducing agents) exceeding 20 MW are operated: Carbon dioxide.

https://ec.europa.eu/clima/policies/ets_en

Consolidated text: Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC

The European aluminium production has a lower carbon footprint versus imports (see Table 2). The Carbon Border Adjustment Mechanism (CBAM) of the European's Green Deal ([38]) may cover the entire aluminium's value chain (primary aluminium and downstream). The mechanism could decrease the carbon footprint of the aluminium consumed in the EU and capitalise on European producers' advantage against carbon-intensive imports.

Box 3. The Carbon Border Adjustment Mechanism

The Carbon Border Adjustment Mechanism initiative (CBAM), a key element of the European's Green Deal, seeks ways to address the risk of "carbon leakage", i.e. the risk that the EU's efforts to mitigate greenhouse gas (GHG) emissions is undermined by a lack of climate ambition in non-EU countries, e.g. by moving operations to avoid carbon costs. Such a mechanism could motivate foreign producers and EU importers to reduce their carbon emissions while ensuring a level-playing field conducive to trade in a WTO-compatible way ([39]). CBAM aims to regulate GHG embedded in specific products of carbon-intensive sectors in the form of carbon pricing upon their importation into the European Union in order to reflect more accurately their carbon content. The European Commission undertook a public consultation in relation to the introduction of the CBAM, and the regulatory proposal is planned for the second quarter of 2021.

EU Green Deal (carbon border adjustment mechanism)

([36]) The share of 8% comprises an energy mix of coal, natural gas, oil and other non-renewable.
([37]) Figures include emissions in a cradle to gate approach (from bauxite to primary ingot casting, including transport) in Europe (EU+UK+EFTA).
([38]) COM(2019) 640 final.
([39]) COM(2020) 6690 final.

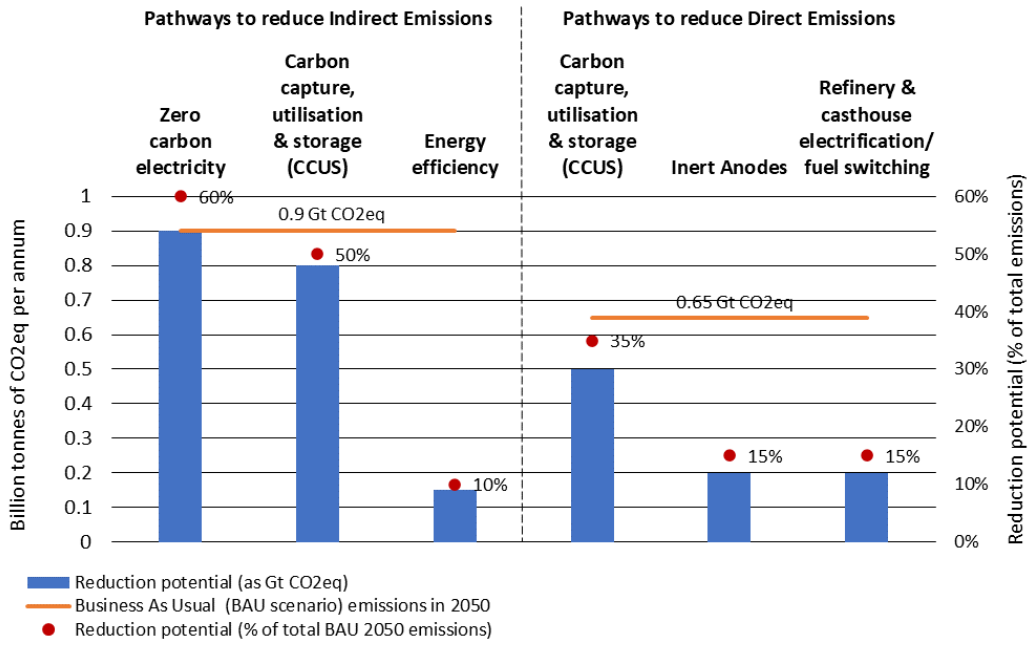
European Parliament resolution of 10 March 2021 towards a WTO-compatible EU carbon border adjustment mechanism

3.1.2 Decarbonisation of primary aluminium production

According to the International Aluminium Institute, global demand for aluminium will increase by up to 80% by 2050 driven by population and economic growth (IAI, 2021b). This demand will be met by both primary and recycled metal. Aluminium has many long-lived applications, such as in construction, thereby lowering availability for recycling for a long period of time. Despite increased recycled metal supply over the coming decades, primary production will continue to be the key contributor for meeting demand, even at 100% recycling rates at end-of-life (IAI, 2020a)(Hund *et al.*, 2020). The International Aluminium Institute (IAI) estimates that up to 90 million tonnes of primary aluminium will be required globally per annum in 2050 (IAI, 2021b).

While recycling can play a significant role in achieving a lower carbon footprint for aluminium production, the decarbonisation of primary aluminium production is the key to reduce the overall aluminium sector's GHG emissions. In line with International Energy Agency's 'Beyond 2 Degree Scenario' (B2DS), the International Aluminium Institute projects that by mid-century the industry would need to reduce its total emissions to 250 million tonnes of CO_2eq, from a 1.1 billion tonnes of CO_2eq in 2018 and a projected 2050 'Business as Usual' scenario of about 1.6 billion tonnes CO_2eq. In the B2DS scenario, indirect emissions associated with electricity production would reduce near zero by phasing out fossil fuels or through carbon capture, utilisation and storage (CCUS) when fossil fuels would be still used. The remaining 250 million tonnes of CO_2eq under B2DS represent direct emissions of smelting, and smaller contributions from mining, transport and ancillary materials (IAI, 2021b). As shown in the following figure, decarbonised power generation and the deployment of CCUS offer the largest potential for aluminium sector GHG emissions reduction (IAI, 2021b).

Figure 23. Aluminium sector greenhouse gas pathways to 2050



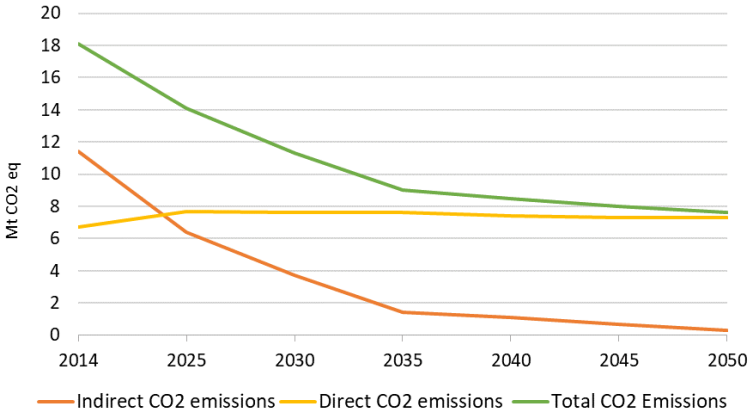
Source: Background data in (IAI, 2021b)

GHG emissions associated with the electrolytic smelting process are much more significant (over 60% of the total) relative to other processes in the value chain (see Figure 14). Therefore, a low-carbon electricity sourcing and improved energy efficiency are two of the pathways to consider in order to decrease the carbon footprint in primary aluminium smelting. The former has a much more significant impact on final carbon intensity, making aluminium production cleaner in countries with a low-carbon electricity mix, whereas the latter will require efforts by the smelting plants themselves to cut their own emissions (Carbon Trust, 2020).

According to projections prepared for the European Aluminium Association (European Aluminium, 2019d), the decarbonisation of the power mix will be the main driver for lowering the carbon intensity of the primary aluminium sector in Europe, as the indirect CO_2 emissions are expected to fall by 97% in 2050 from the 2014

levels. The association's study forecasts that the European power sector's decarbonisation will eliminate 58% of the industry's remaining total emissions in 2050 compared to 2014 (Figure 24). The carbon intensity of primary aluminium smelting in the EU+UK+EFTA is forecast to fall from 4.5 kg CO_2eq per kg of primary aluminium in 2014 to 1.7 kg CO_2eq in 2050 due to the greater use of zero-carbon sources in the power mix of Europe.

Figure 24. Evolution of direct, indirect and total CO_2 emissions from primary aluminium smelting in EU+UK+EFTA, 2014-2050 ([40])



Source: Background data in (European Aluminium, 2019d).

Improvements in energy efficiency within existing smelting technologies will not be enough for a drastic reduction of carbon emissions by 2050 from European smelters. Major innovation efforts to revolutionise the smelting process are needed to go beyond the existing processes' limits and move primary aluminium production towards carbon-neutrality. Full-scale demonstrators, requiring significant investments, are necessary to demonstrate feasibility and profitability of such innovation prior to full-scale deployment (European Aluminium, 2020a) (European Aluminium, 2019d). The following box presents cutting-edge, low-carbon technologies under development in primary aluminium's production route worldwide.

Box 4. Innovation in aluminium smelting technologies

ELYSIS: Two major industry players - Rio Tinto and Alcoa – formed in 2018 a joint venture to develop an inert anode and commercialise the carbon-free smelting process by 2024. The technology is being developed and scaled up in Canada. The ELYSIS technology effectively puts an end to the use of carbon anode through newly developed, breakthrough proprietary materials that do not degrade during the process and, thus, do no produce process emissions. The technology produces only oxygen as a by-product, eliminating all direct greenhouse gases emissions attributable to carbon anode consumption in the traditional aluminium smelting process (ELYSIS, no date).

HAL4e: This new potline technology developed by Hydro will use about 15% less energy for aluminium production than the global average. In particular, 48 out of the 60 cells in the Karmøy Technology Pilot in Norway operate with an energy consumption of 12.3 kWh/kg aluminium, whereas the world average is 14.1 kWh/kg. Meanwhile, 12 cells (HAL4e Ultra cells) are installed based on the identical technology platform as the HAL4e cells, but for the purpose of implementing new technology elements with a lower technology readiness level. The HAL4e Ultra cells are expected to operate with an energy consumption of 11.5-11.8 kWh/kg aluminium, which is the lowest energy consumption ever achieved. In addition, the world's most energy-efficient aluminium production will be matched with high productivity, i.e. about 50% higher than other modern Hydro's plants. The HAL4e technology will enable the lowest CO_2 footprint in the world, and direct CO_2eq emissions will be 0.8 kg lower per kilo of aluminium than the world average (Hydro, 2019)

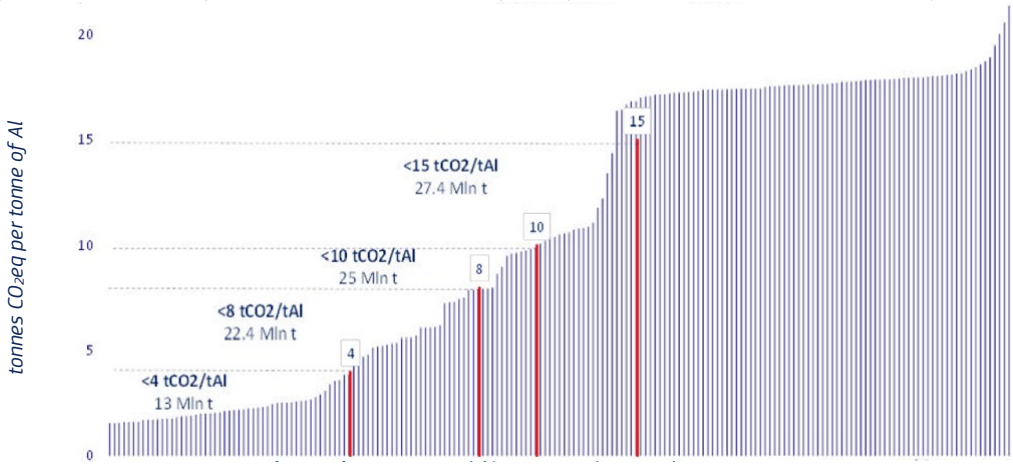
KrAZ: RUSAL's Krasnoyarsk plant (KrAZ) in Russia has already produced primary aluminium using inert anode technology at an industrial scale. Inert anodes replace standard carbon anodes with inert, non-consumable

([40]) Modelling was based on the IEA's 2DS scenario for indirect CO_2 emissions and constant 2014 carbon intensity for direct emissions.

materials – ceramics or alloys, which results in a major reduction of emissions from the smelting process (less than 0.01 metric tons of CO2 equivalent per ton (Rusal, 2021)(Aluminium Insider, 2021).

The figure below shows the current distribution of smelters' carbon intensity globally. Producers' carbon footprint ranges from about 2 to 20 tonnes CO_2eq per produced tonne of aluminium. Over half of the total production volume has a carbon footprint of around 17 tonnes CO_2eq per tonne of metal produced. The value of 4 t CO_2eq/t Al is a threshold proposed for setting up the low-carbon ([41]) aluminium label, covering approximately 20% of global aluminium production in 2018 (Carbon Trust, 2020). Producers at the lower end of the curve run their smelters using hydropower rather than fossil fuel, which dramatically reduces the impact. However, common standards for carbon calculation and clear labelling are needed to define the so-called 'green' aluminium to empower consumers with transparent and substantiated information amidst competing claims about carbon footprint by various commercial brands of low-carbon aluminium (Carbon Trust, 2020).

Figure 25. Carbon footprint ([42]) distribution of world primary aluminium smelters, in 2018, total production 63.3 Mt



Source: (Carbon Trust, 2020) based on CRU data.

3.1.3 Contribution to energy efficiency and low-carbon technologies

Aluminium is an essential contributor to energy-efficient applications and low-carbon energy generation technologies due to its specific properties such as lightweight and strength, heat and electrical conductivity, corrosion-resistance, recyclability, and formability. The benefits enabling other sectors to reduce their carbon emissions are listed in the following paragraphs.

3.1.3.1 Transport

Transport is one of the largest energy-consuming sectors, responsible for 24% of direct CO2 emissions worldwide from fuel combustion ([43]). Increased aluminium use in the transport sector – for instance, in cars, boats and aviation – would achieve improved fuel efficiency and carbon emissions reduction without compromising safety.

As an indicative case study, Figure 26 looks at the effect of light-weighting in a typical internal combustion engine (ICE) gasoline vehicle by replacing 100 kg of mild steel with aluminium or advanced high-strength steel (AHSS). In order to calculate the benefits of light-weighting in total greenhouse gas emissions, the full lifecycle (materials production, vehicle production, vehicle use phase, and end-of-life stage) is taken into account. The results originate from the Automotive Life Cycle Model developed by the International Aluminium Institute and European Aluminium (Bertram et al., 2019).

([41]) According to (Material Economics, 2018), the carbon intensity for primary aluminium production based on CO_2-free power is considered at 3 tonnes CO_2eq per tonne.
([42]) Direct emissions (Scope 1) & indirect emissions from energy (Scope 2).
([43]) https://www.iea.org/reports/tracking-transport-2020

Figure 26. Indicative comparison of the impact of different material selections for weight reduction of typical passenger cars ([44]), bill of materials (top) and GHG emissions (middle and bottom)

Source: Outputs from (European Aluminium-IAI, 2019).

The net life-cycle savings of substituting 100 kg of aluminium for mild steel in the baseline vehicle is about 5 grams of CO_2eq per kilometre travelled, or about 1 tonne of CO_2eq in the lifetime of an average family car, i.e. 200,000 km. Comparing aluminium with advanced steel grades in car manufacturing results that using 100 kg of aluminium instead of AHSS saves 322 kg of CO_2eq in the vehicle's lifetime (including credits of end-of-life

([44]) The Life Cycle model compares a baseline car model with two lightweight versions. The lightweighting can be achieved with Advanced High Strength Steel (AHSS), with Aluminium or with a combination of the two. In this indicative example, extruded aluminium is considered for the replacement of 100 kg of mild steel

management). However, as the share of the lightweight materials used by the automotive industry is growing fast, cost is an important factor that determines the lightweight materials use pattern. For example, high-strength steel is 20% lighter than steel in parts used in automotive applications and had an additional cost of 15% in 2010, use of aluminium offers a weight advantage of 40% over steel parts but was 30% more expensive, whereas carbon fibre is 50% lighter compared to steel but was available at a cost of five to six times as high as steel in 2010 (McKinsey, 2012).

Moreover, the e-mobility revolution foresees growth in aluminium intensity in vehicles due to the reconfiguration of new parts within a vehicle and a focus on weight reduction, such as in structural battery enclosures and e-motors housing (Hogna, 2018) (CRU, 2018). CRU estimated that the aluminium intensity in electric vehicles is about 25-30% higher compared to a typical internal combustion engine car (CRU, 2018).

3.1.3.2 Construction

The construction and buildings sectors combined consume over one-third of the world's energy demand and nearly 40% of total direct and indirect CO_2 emissions worldwide ([45]). Aluminium properties are exploited in buildings improving energy efficiency, notably via windows, curtain walls and aluminium-based facades (European Aluminium, 2019b). The recyclability and durability of aluminium improves further buildings' sustainability and emissions reduction. Aluminium's recycling rates from construction applications are reported in the order of 80%-90%, and aluminium's use in buildings and construction offers long service life without the need for maintenance (European Aluminium, 2019d) (Euromines, 2019) (Eurometaux, 2015). According to industry's claims, the energy needed to construct an aluminium-based building (embedded energy) is higher than for most other materials but small compared to the lifetime energy consumption and the energy-saving potentials (Hydro, 2012).

3.1.3.3 Packaging

Environmental benefits of using aluminium in packaging derive from weight reduction, hence reducing the energy required for transportation and transport-related CO_2 emissions (European Aluminium, 2014)(GDA, 2017). Material savings through the downgauging achieved for aluminium beverage cans in the past – from 6 kg of aluminium used for 1,000 beverage cans in 1984 to 13 kg in 2011 and foil – thicknesses for various foil applications have been reduced up in the range 28-40% from 1974 to 2014 – contributed further to the benefits of light-weighting (European Aluminium, 2014). In addition, aluminium's high thermal conductivity reduces the energy requirement for hot sealing and sterilisation, along with freezing, cooling and heating in the pack (GDA, 2017). Moreover, aluminium's food preservation properties contribute to less food products' waste due to degradation (European Aluminium, 2014). Finally, the high recycling rates achieved for metal packaging ([46]) saves raw materials and reduces energy consumption and CO_2 emissions (see Section 6).

3.1.3.4 Low-carbon energy technologies

Wind turbines, solar power installations, Li-ion batteries for energy storage and traction motors for e-mobility are among the low-carbon technologies requiring aluminium.

In wind turbines, aluminium is used as a lightweight material in nacelle equipment, blades, etc. In particular, several tonnes of aluminium may be required in parts such as the gearbox, while blades and cores within wind turbines utilise materials based on aluminium honeycomb technology combining high strength and low weight. The aluminium usage across different turbine types is estimated to range widely between 500 – 1,600 kg per MW (Carrara *et al.*, 2020). The lower estimates apply to direct-drive turbines where copper is the preferred material and possibly stem from different requirements for onshore and offshore wind turbines. In addition, they might also represent to a certain extent the selective replacement of copper with aluminium in the cast-coil transformer in the nacelle or in the tower design. Some leading European manufacturers have already adopted cast-coil aluminium transformers in the nacelle reducing overall copper usage intensity by 27% (from 3,500 Kg/MW with a Cu cast coil to 2,500-3,000 Kg/MW with an aluminium cast-coil). The replacement of copper by aluminium lowers the turbine cost but presents some challenges due to lower strength, relaxation behaviour and corrosion resistance ((BBF Associates and Kundig, 2011) in (Carrara *et al.*, 2020)). Besides the

([45]) https://www.iea.org/topics/buildings

([46]) According to Eurostat packaging waste statistics in the EU, the recycling rate was 82.9% for metal packaging in 2018, whereas the average recycling rate for all packaging materials was 66.3%. https://ec.europa.eu/eurostat/statistics-explained/index.php/Packaging_waste_statistics

turbine itself, aluminium is also used for the production of cables at the wind power plant site (Carrara *et al.*, 2020).

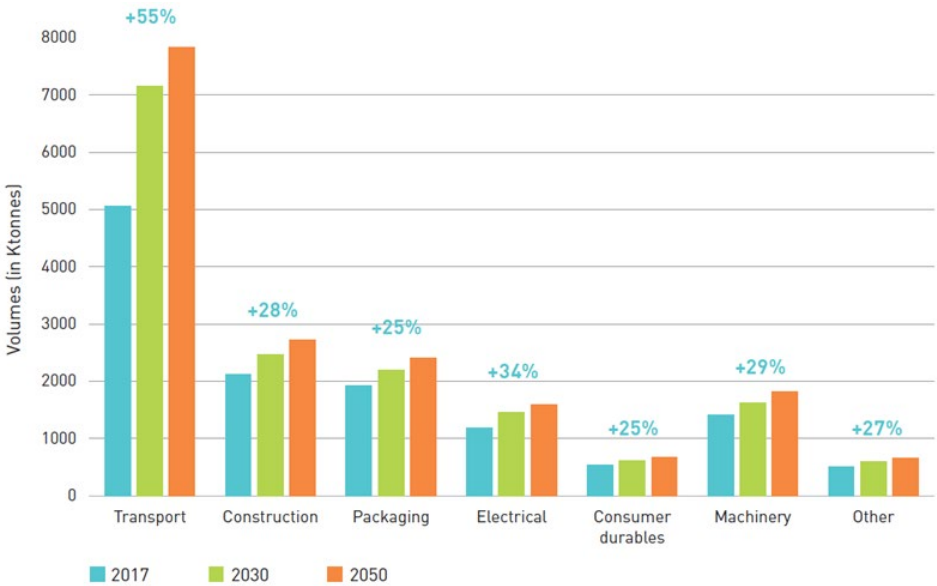
In solar PV technologies, aluminium is used in panel frames and inverters or for construction and support (European Commission, 2020). The material intensity is reported 7.5 tonnes per MW(Carrara *et al.*, 2020). In Li-ion batteries, aluminium is used for battery packaging and as current collector foil (cathode), as well as in NCA (Nickel Cobalt Aluminium oxide) batteries (European Commission, 2020). In traction motors for e-mobility, aluminium is used in casings and as lightweight material in other metallic parts (European Commission, 2020). Finally, solar thermal collectors require aluminium for absorbers, casings and frames (Euromines, 2019).

Furthermore, aluminium is becoming the preferred material for high and extra-high voltage submarine transmission cables, which will play a significant role in connecting northern and southern Europe, ensuring a more liquid electricity market by transporting renewable energy to where it is needed (European Aluminium, 2019d).

3.1.3.5 Future demand

All these characteristics explain the projected accelerated growth in demand for aluminium. The European Aluminium Association forecasted the average growth rate of semis consumption in Europe to 39% from 2017 to 2050 (European Aluminium, 2019d). Environmental considerations will be the drivers of the increasing demand for aluminium in applications where aluminium's properties can deliver environmental benefits. The demand for transport in order to reduce vehicle emissions, for construction driven by the need to increase energy efficiency in buildings, and for recyclable light packaging is expected to increase by 55%, 28% and 25%, respectively in 2050 compared to 2017 (Figure 27).

Figure 27. Demand for semi-finished aluminium in Europe per sector in the year 2017, 2030, and 2050



Source: (European Aluminium, 2019d) based on CRU data.

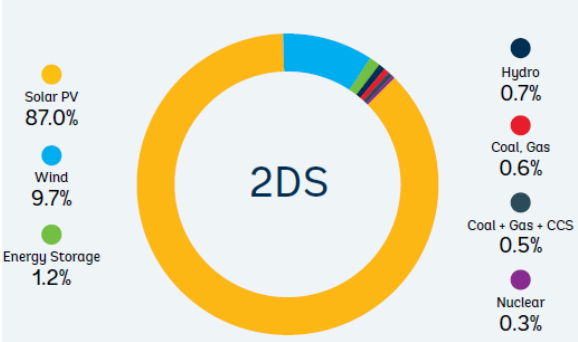
A recently published study by the World Bank estimated the future demand for aluminium in clean energy technologies (Hund *et al.*, 2020). Figure 28 shows the identified low-carbon technologies that require aluminium. The study concluded that annual aluminium demand worldwide for a broad range of energy technologies ([47]) would need to grow significantly by about 5.5 Mt in 2050, which is the highest absolute increase in terms of quantity compared to all materials ([48]) analysed in the study after iron. However, the projected growth of demand is small in percentage terms, i.e. 9% compared to 2018 production levels for the scenario to keep global warming below 2 C^0 (Hund *et al.*, 2020). The study also demonstrates that solar PV technologies will

([47]) The study addressed certain electricity generation and energy storage technologies, excluding the new infrastructure required for the low-carbon transition

([48]) Chromium, Cobalt, Copper, Graphite, Indium, Iron, Lead, Lithium, Manganese, Molybdenum, Neodymium, Nickel, Silver, Titanium, Vanadium, Zinc

account for most aluminium demand growth (87% of demand from solar PV). Another recent study by the Joint Research Center estimated the global demand of aluminium in PV to be around 11% in 2050 in comparison to the current global supply, whereas for wind power this is estimated to be below 1% ([49]).

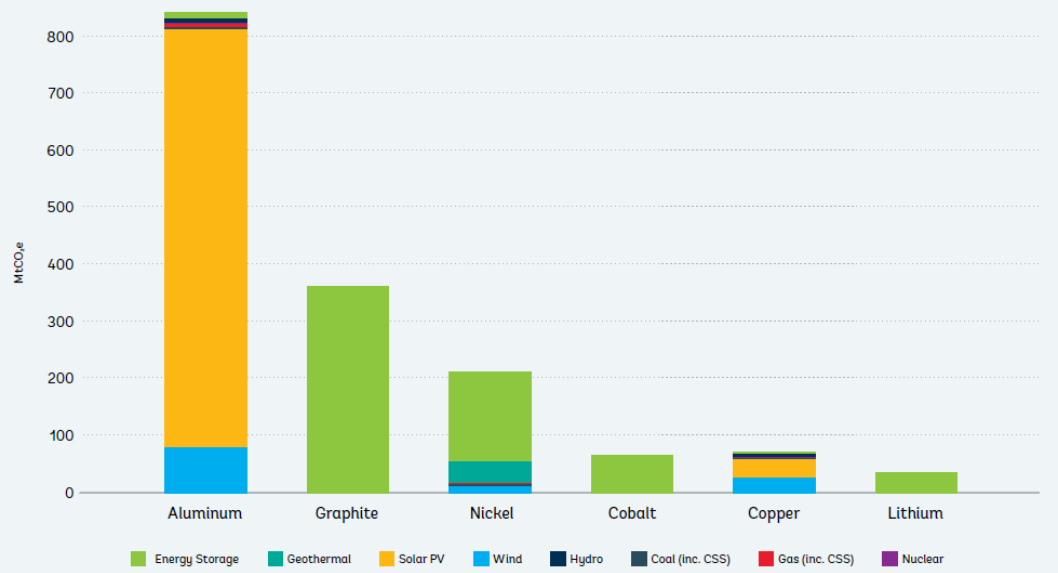
Figure 28. Total aluminium demand by energy technology through 2050 under 2DS scenario ([50])



Source: (Hund *et al.*, 2020).

Simultaneously, carbon emissions associated with the increased aluminium production are projected as the most substantial among all minerals needed for the clean energy transition (Figure 29). The carbon intensity of aluminium production is a challenge that should not be overlooked in the deployment of renewable energy supply chains. Nevertheless, the study highlights that emissions from the production and operation of mineral intensive low-carbon technologies account in total only for a fraction (6%) of emissions generated by conventional fossil fuel technologies (Hund *et al.*, 2020).

Figure 29. Cumulative Global Warming Potential from extraction and processing of minerals for renewable energy and storage technologies, cradle-to-gate through 2050 under 2DS



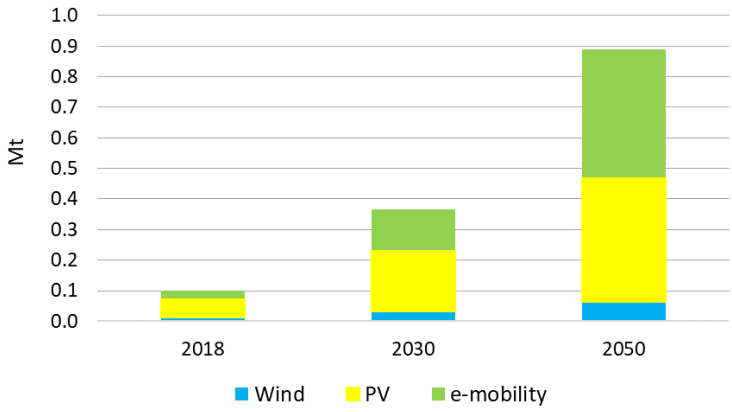
Source: (Hund *et al.*, 2020).

([49]) The considered electricity generation scenario is consistent with limiting future temperature increases to 1.5 °C and 100% electricity supply from renewable energy resources in 2050.

([50]) 2DS = 2-degree scenario developed by the International Energy Agency (IEA) in 'Energy Technology Perspectives 2017'. Scenario with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100.
CCS = carbon capture and storage
PV = photovoltaic

Significant volumes of aluminium needed in the EU up to 2050 are also projected by a recent European Commission's study ([51]) based on the EU's 2050 climate-neutrality scenarios, even though the additional demand is small (<10%) compared to the current EU share of global supply (Figure 30).

Figure 30. EU annual aluminium demand ([52]) for renewables (wind power and photovoltaic) and e-mobility (traction motors) towards 2050



Source: Data from (European Commission, 2020).

([51]) The study covered aluminium demand for growing technologies in clean energy (photovoltaic, wind) and e-mobility (in traction motors). The potential increased usage of aluminium in the design of new parts in electric vehicles is not accounted.

([52]) Medium-demand scenario (MDS).

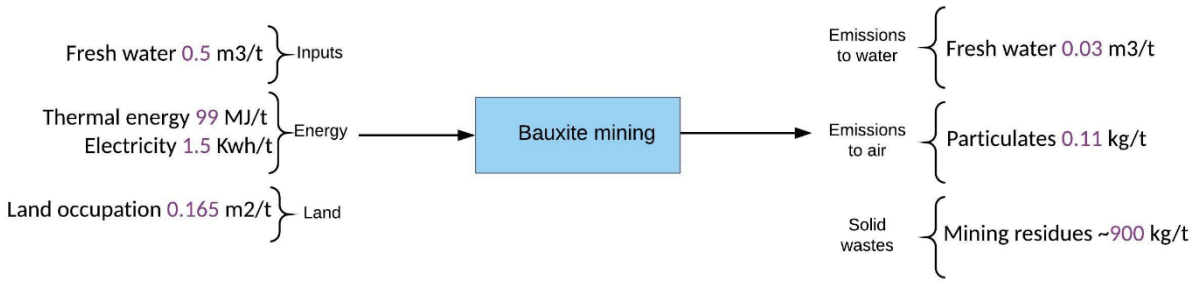
4 Environmental aspects

4.1 Environmental considerations for bauxite mining

4.1.1 Emission and consumption levels

The following figure shows the main inputs and outputs for the production of 1 tonne of bauxite ready for delivery to an alumina plant.

Figure 31. Consumption and emission levels for the production of one tonne of mined bauxite, world, 2015 data



Source: Background data in (European Aluminium, 2018b)(IAI, 2017) (Garbarino et al., 2018).

The biggest environmental challenge that bauxite mining faces is the requirement of large land zones. In addition, bauxite mines often operate within or close to areas of high biodiversity and ecosystems value in tropical and sub-tropical zones (see Section 4.1.3). On the basis of the data on land occupation shown in Figure 31, bauxite mining operations used about 55 km^2 of the land area throughout the world in 2018. Concerning the volume of extractive residues associated with bauxite production, the average residue-to-product ratio is reported to be 2.5 in the literature, whereas the ratio ranges from 0.1 to 1.6 (average 0.8) for underground mines in the EU according to site-specific data (Garbarino *et al.*, 2018).

4.1.2 Environmental background conditions of mining activities

This Section provides an overview of the environmental hazard potential due to bauxite's geology and prevailing mining practices, the environmental impact that bauxite mining activities might entail on water resources, and the risks originating from natural disasters.

4.1.2.1 Geology and mining practices

Most of the world's bauxite comes from surface mines. 95% of the bauxite's mining capacity worldwide operates in open-pit mines([53]). Bauxite mines are predominantly found in tropical and subtropical areas, where bauxite typically occurs in extensive, relatively thin layers near to the surface, generally beneath a few meters of overburden (IAI, 2018b). The overburden layers of rock and clay above the bauxite deposit are typically in the range 0-20 meters; on average, overburden thickness is around 2 meters (IAI, 2020b). The bauxite layer thickness may range from 1 to 40 meters in exceptional cases, but it is typically 4-6 meters. The near-surface horizontal layers of bauxite extent over an area that may cover tens or even hundreds of square kilometres (IAI, 2018b). Strip-mining methods are commonly applied to remove topsoil, subsoil and overburden overlying the bauxite. The rich in organic matter topsoil is typically reused for rehabilitation (IAI, 2020b), preferably immediately after stripping to other mined-out areas to retain its value as a seed source and growing medium; hence, maximising the success of revegetation. Otherwise, it is stockpiled and used for reforestation afterwards (IAI, 2018b).

As a consequence of the morphology and depth of bauxite deposits, bauxite mining disturbs comparatively larger land areas compared to the mining of other minerals, though for a shorter time (IAI, 2018b). This is due to the relatively easy rehabilitation and recultivation of the mined area for the same reasons that result in the requirement of large areas for mining. Hence, the overall disruption is relatively smaller compared to other types of open cast mining as the land area exposed at any one time is effectively limited (IAI, 2020b). A survey

([53]) See Annex 1 on the methodology applied and data sources used for the calculation of mine capacities

conducted in 2008 by the International Aluminium Institute([54]) concluded that the rehabilitated area in global bauxite mines over 2002-2006 equaled in size the newly mined area. In 2006, 53% of the used areas had already been rehabilitated, while the remaining 47% was still being mined or devoted to infrastructure purposes (IAI, 2009). The study also determined that typically one square meter of land was mined annually on average (together with the required infrastructure) per tonne of aluminium. Consistent with this ratio, the land area mined for bauxite throughout the world is estimated at around 60 km^2 per year.

Unlike other base metal ores, bauxite is marketed without any significant beneficiation, or it can even be directly shipped after mining. Simple mineral processing techniques, i.e. crushing, washing, drying and screening, can be applied to remove clay and fine sands before shipment to alumina refineries or other markets. Beneficiation reduces the amount of material that needs to be transported and processed at the refinery; however, these benefits need to be weighed against the amount of energy and water used in the process and the management of the fine wastes produced (IAI, 2020b).

Considering the geological features and the mining practices presented in Table 1, the environmental hazard potential of mining sites and mined bauxite confirms that the most concerning aspect related to the bauxite mining practices is the mine type.

Table 1. Environmental Hazard Potential related to bauxite's geological features and mining practices ([1])

Indicator	Assessment of environmental hazard potential	Explanation	Data quality
Environmental hazard potential related to geological features			
Preconditions for acid mine drainage (AMD)	Low	According to the Goldschmidt geochemical classification, aluminium is a lithophile element readily combined with oxygen. Bauxite is an oxidic ore consisting mostly of the aluminium minerals gibbsite ($Al(OH)_3$), boehmite (γ-AlO(OH)) and diaspore (α-AlO(OH)), mixed with iron oxides. Therefore, geochemical preconditions for Acid Mine Drainage (AMD) do not exist in bauxite mining	High
Paragenesis with heavy metals	Medium	The main constituents of bauxite are Al hydroxides and Fe oxides (not heavy metals). However, bauxite deposits may contain slightly elevated concentrations of heavy metals.	Medium
Paragenesis with radioactive substances	Medium	Average data on Chinese bauxite deposits (about 21 % of world production in 2018) suggest that in many cases aluminium is associated with slightly elevated concentrations of uranium and/or thorium	Medium
Environmental hazard potential related to mining practices			
Mine type	High	Bauxite is a bulk commodity extracted mainly from weathered, near-surface horizons in tropical regions; therefore, mining frequently requires access to large land zones.	High
Use of auxiliary substances	Low ([2])	No toxic auxiliary substances are used for bauxite mineral processing.	High

([1]) Annex 2 presents the evaluation method for the Environmental Hazard Potential
([2]) UBA's study assesses the use of auxiliary substances as 'Medium' as the use of caustic soda for the further processing of bauxite into alumina (Bayer process) is taken into account

Source: Adapted from (Dehoust et al., 2020).

([54]) The collected data from bauxite mining companies represented 66% of the world's total bauxite production in 2006

4.1.2.2 Water

An important point to highlight the environmental impact of a commodity's extraction is water use. Data on water use collected by (Mudd, 2008) from sustainability reports published by a set of mining companies worldwide([55]) also covered bauxite mining. According to this dataset, which includes 17 years, water consumption in bauxite mining, concerning ore throughput, averages 1.09 m^3 per tonne of ore (with a standard deviation of 0.44). More recently, the International Aluminium Institute, based on data from a 2015 survey, reported a world average water input of 0.5 m^3 of freshwater necessary to extract and prepare one tonne of bauxite (IAI, 2017). Still, the sustainability of bauxite mining concerning its water use will depend on water risk where the operation is located (see Figure 32).

Box 5. The Water Risk Index

The Water Risk Index, developed by the World Resources Institute, measures water-related risks, by aggregating 13 selected indicators concerning various types of risks, namely:

- the **physical quantity** of water (water stress, water depletion, interannual variability, seasonal variability, groundwater table decline, riverine flood risk, coastal flood, and drought risk);

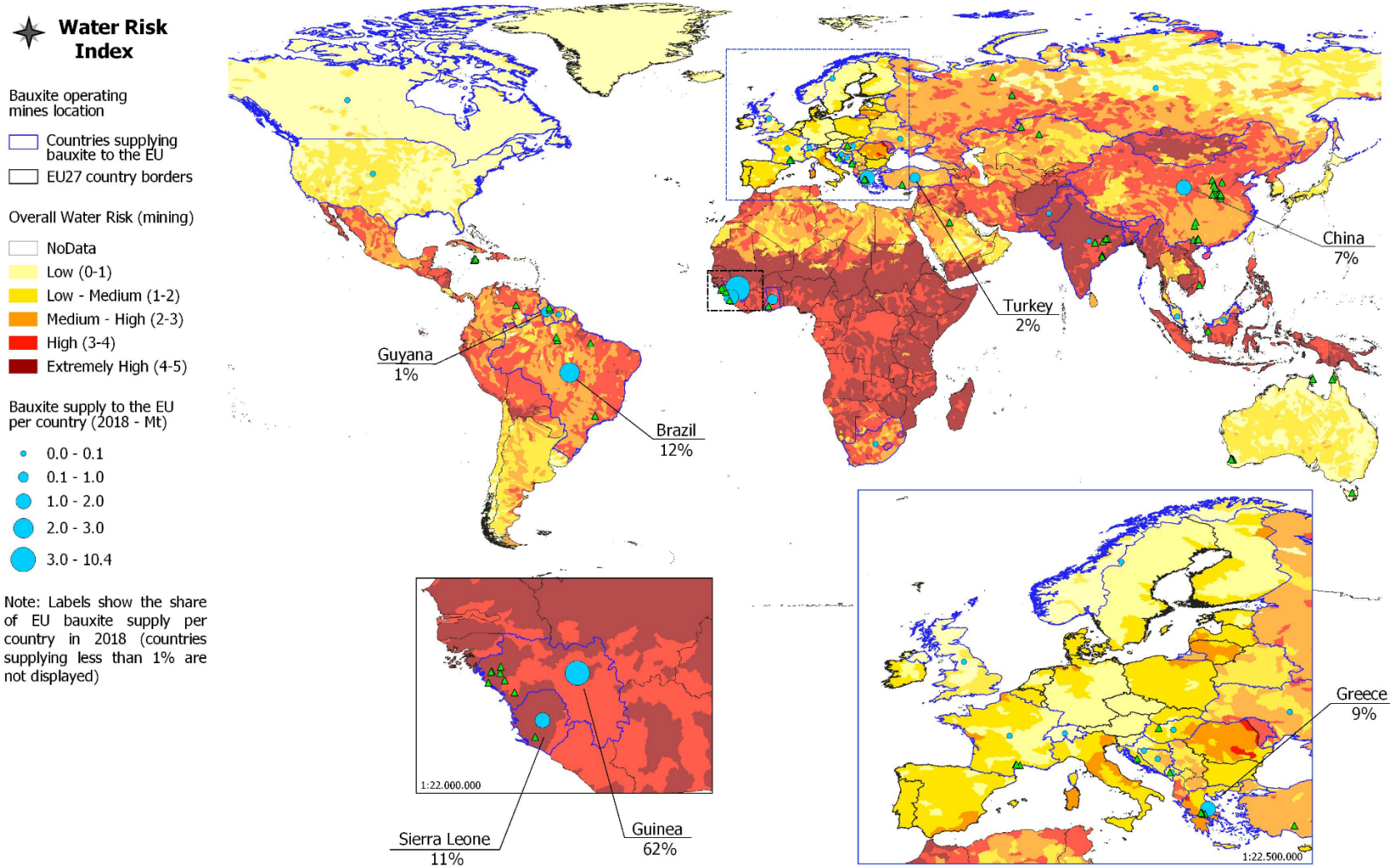
- the **physical quality** of the water (untreated wastewater, and coastal eutrophication potential);

- **regulatory and reputational risk** (drinking water and sanitation conditions, as well as business conduct risk exposure related to environmental, social, and governance issues).

Indicators can be combined using different weightings for different economic sectors. Data providers include a calculation of the index weighted to mining activities. This weighting gives more relevance to specific physical water quantity risk indicators such as flooding or droughts and reputational and regulatory water risks. Also, it gives less weight to water quality considerations (Hofste et al., 2019). Higher values of the index indicate higher water risk.

([55]) Global Reporting Initiative (GRI) https://www.globalreporting.org/

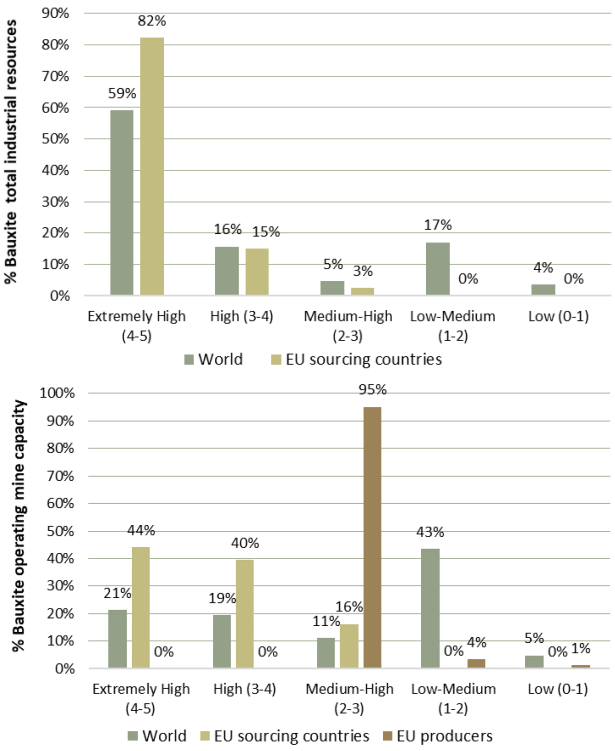
Figure 32. Water Risk Index weighted to mining activities and operating bauxite mines in countries supplying bauxite to the EU



Source: JRC elaboration based on (World Resources Institute, 2019) for the Water Risk Index; (Reichl and Schatz, 2020) for bauxite production; (Eurostat, 2020b) for imports;(S&P Global, 2020) and various other sources for mines' location and operating status.

84% of the capacity of operating bauxite mines in countries from which the EU sources bauxite is located in places with water risk ranging from high to extremely high. In comparison, the world average is 40% in high and extremely high-risk areas (Figure 33). Most EU bauxite mines are located within medium-to-high water risk areas and none under high or extremely high-water risk. When interpreting these results, it should be considered that although the water risk index depicts the annual situation, some of the water quantity risk indicators rather vary over the year, with waters stress peaking in southern EU during the summer period.

Figure 33. Percentage of industrial bauxite resources (incl. reserves) ([56]) (top) and operating bauxite mine capacity ([57]) (bottom) within areas with a different water stress level



Source: JRC calculation

Moreover, according to results published by WWF (The Water Filter Risk([58])), bauxite faces slightly above the average water risk levels than other minerals (Morgan and Dobson, 2020). For bauxite mining, reputational and regulatory water-related risks were the largest, while flood risk was the largest component of the physical water risk([59]).

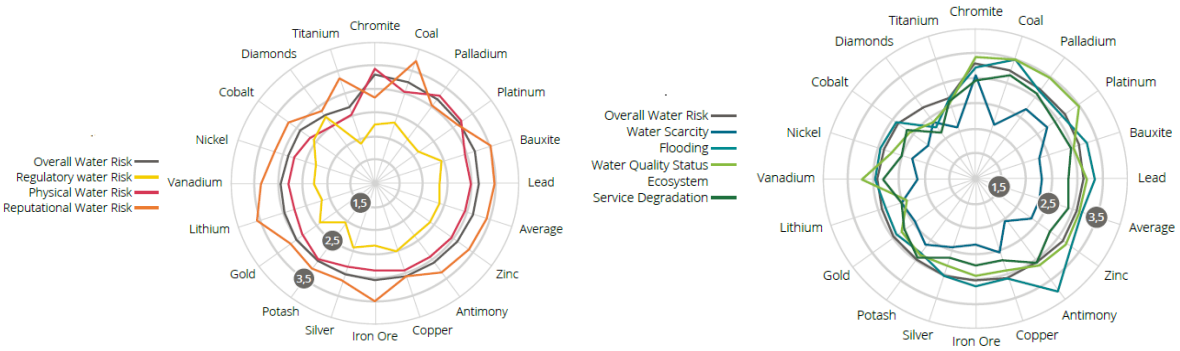
([56]) Industrial resources (including reserves) refer to mines, exploration and mine development projects regardless of activity and development status. They do not comprise resources in not exploited or not explored deposits.

([57]) Annex 1 describes the applied methodology and data sources for calculating mine capacity.

([58]) Details on the data and methods of the Water Filter Risk are available in https://waterriskfilter.panda.org/en/About/DataAndMethods.

([59]) The study concluded that all commodities in the mining sector have a moderate level of water risk exposure. While no commodity is very highly exposed to water risks, conversely, no commodity is exposed to very low water risks either. Bauxite has a higher or similar exposure to water risks than other commodities except for chromite, platinum and palladium.

Figure 34. Spider diagram of basin water risk by mining commodity per broad risk categories (left) and physical risks (right)



Source: (Morgan and Dobson, 2020).

Another publication by (Northey et al., 2014), based on the Water Stress Index by (Pfister et al., 2009) and supplemented by desert area provided by (Olson et al., 2001), found that 10% of bauxite mines are in environments that exceed the average water stress. Finally, a study by (Dehoust *et al.*, 2020) - also based on a water stress indicator, supplemented by desert areas classified by WWF - found that 28% of bauxite mines worldwide were located in high water-stress risk areas while the remaining in areas with low water stress.

4.1.2.3 Natural hazards

The risk index of natural disasters for Guinea and Sierra Leone, which supplied respectively 58% and 10% of the total bauxite supply to the EU in 2018, is very high (see Figure 36). The high values derive mostly from substantial-high levels of vulnerability, while the exposure level is not that high. Greece, providing 9% of supply, shows better yet also medium risk levels, primarily due to high exposure to extreme events. Other EU supplying countries like Brazil and China (respectively 11% and 7% of EU sourcing in 2018), show low levels of natural disaster risk.

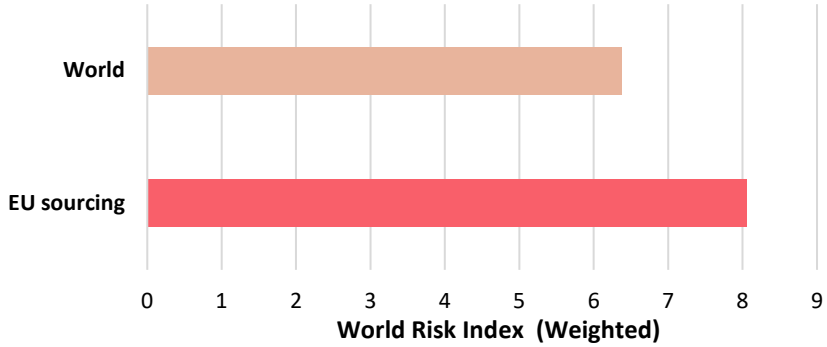
Box 6. The World Risk Index and natural disasters

Raw materials supply can be affected by the occurrence of natural disasters. The fact that an extreme natural event becomes a disaster, and the size of the consequences depends strongly on a society's coping capacity, which considers its framework conditions, structures in place for a quick, effective reaction, etc.

The World Risk Index estimates the risk of disaster caused by extreme natural events by country worldwide. It is calculated through the multiplication of exposure and vulnerability. Exposure covers threats such as earthquakes, storms, floods, droughts and sea-level rise. Vulnerability considers three components (equally weighted): susceptibility, coping capacity and adaptation. Unlike coping, the latter is understood as a long-term process that also includes structural changes in society (Behlert et al., 2020).

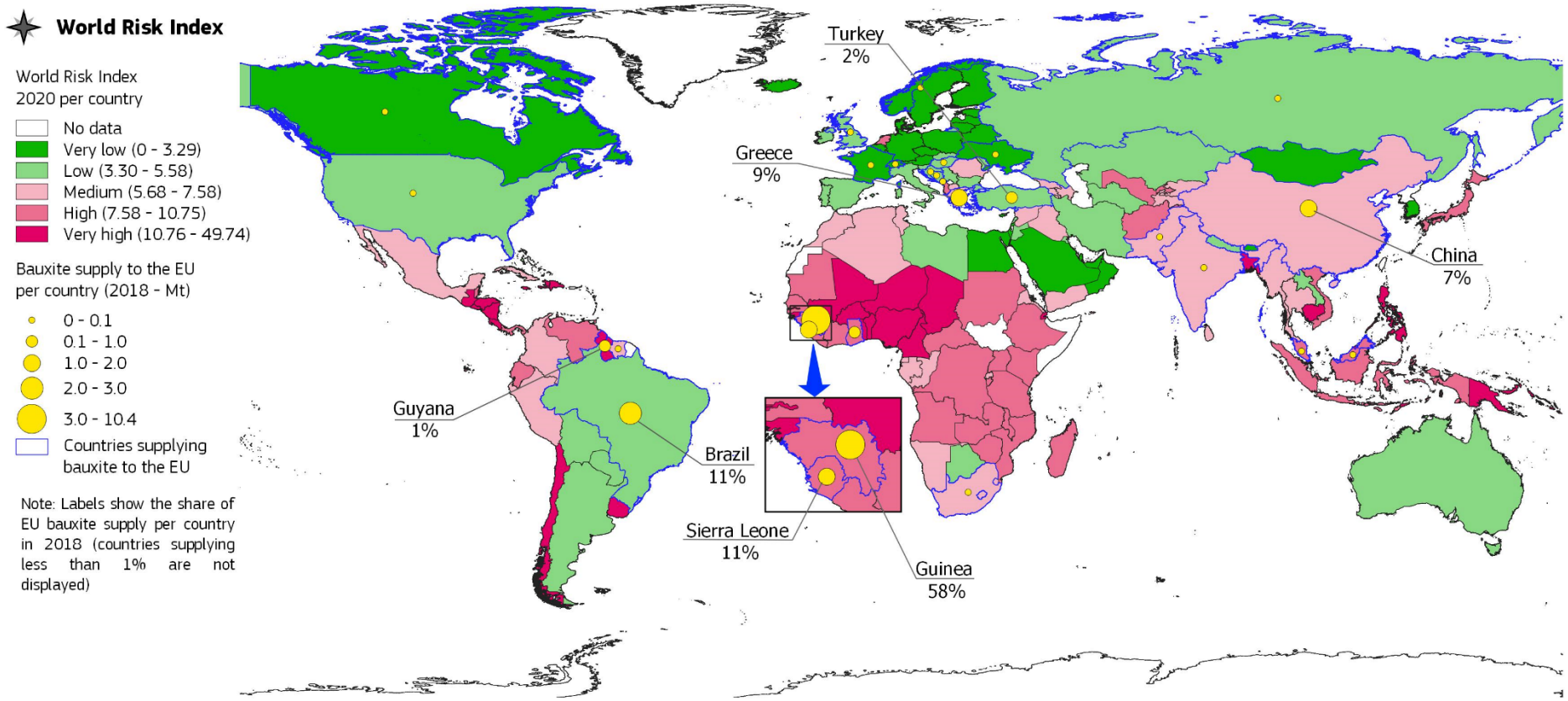
The following figure compares the weighted average index between EU suppliers and world production. The outcome is that the EU supply is subject to a higher risk of natural disasters.

Figure 35. Weighted average World Risk Index (2020 values) for the world and EU supply of bauxite in 2018



Source: Based on data in (Behlert et al., 2020) for the 2020 World Risk Index.

Figure 36. EU sourcing of bauxite (in 2018) and World Risk Index (in 2020) in supplying countries



Source: JRC elaboration based on (Behlert et al., 2020) for the 2020 World Risk Index; (Reichl and Schatz, 2020) for bauxite production; (Eurostat, 2020b) for imports.

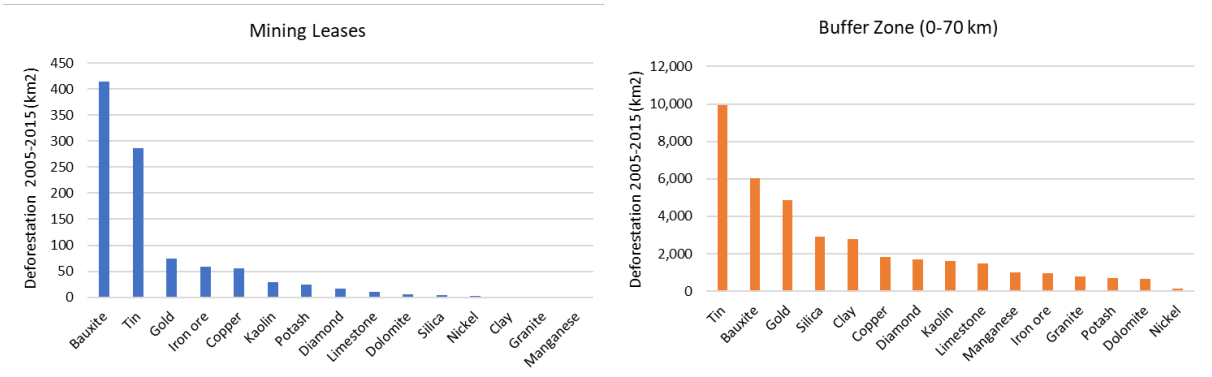
4.1.3 Biodiversity

Bauxite extraction is considered to have a large mining footprint as bauxite mines are mostly opencast, and bauxite deposits often cover a large area. Besides, as the major bauxite deposits worldwide are commonly found in tropical and sub-tropical areas, they often overlap or are adjacent to areas of high conservation value (IAI, 2018b). Therefore, effective mitigation actions on the impacts on ecosystems and biodiversity are critical to achieving a sustainable outcome.

A survey conducted by the International Aluminium Institute found that in 2008 approximately half (49%) of the original vegetation cover before the commencement of bauxite mining was native forest (mostly hardwood), followed by tropical rain forest (24%). A recent World Bank's study on the impacts of large-scale mining on forests suggests that bauxite mines represent 5% of the world's large-scale mines ([60]) in a forested area. The analysis also identified that the bauxite mining industry has the strongest association with forest mines (64% of bauxite mines lie in forests compared to 45% of operational mines for the rest of covered commodities). The country with the highest number of large-scale bauxite mines within forests is Brazil, where reliance on forest bauxite mines is disproportionately high compared to other world producers (World Bank, 2019).

Sonter et al. (2017) quantified mining-induced deforestation in Brazil's Amazon. As data shows in Figure 37, mining drives deforestation far beyond operational lease boundaries (up to 70 km from leases), where deforestation was significantly greater than within leases. The total forest area cleared for mineral extraction between 2005 and 2015 was 983 km^2 on-lease or 14% of the forest area contained in these areas in 2005. Off-lease deforestation amounted to 37,400 km^2 or 11% of the forest area contained in areas surrounding the mining leases (0-70km) in 2005. According to the study (Sonter et al., 2017), of this total deforestation 11,670 km^2 (31%) was induced by mining ([61]), i.e. 12 times greater than that occurring within mining leases alone. Bauxite was the commodity that brought about the most extensive deforestation in Brazil's Amazon forests within mining leases between 2005 and 2015 and was also associated with significant off-lease deforestation (Figure 37).

Figure 37. Mining-induced deforestation in the Brazilian Amazon within mining leases ([62]) (left) and deforestation in the surrounding buffers (0–70 km) impacted by mining ([63]) (right)



Source: Background data from (Sonter *et al.*, 2017).

The following figure shows the extent to which different commodities contributed to deforestation in the Brazilian Amazon between 2005 and 2015 and the average forest loss caused on average in areas impacted by mining in 2005-2015 per commodity. Bauxite mining accounted for 42% of the total forest loss caused by mining activities within leases in the Brazilian Amazon, whereas 16% of the total deforestation in the buffer

([60]) Commodities covered by the study: Bauxite, Iron, Gold, Copper, Manganese, Chromite, Nickel, Zinc, Titanium, Silver.

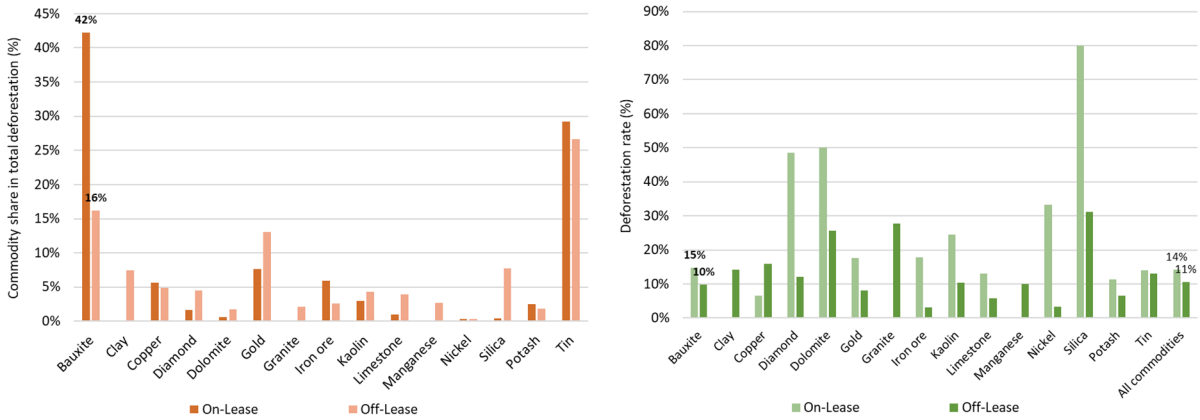
([61]) Mining-induced impacts in off-lease areas include the establishment of mining infrastructure, associated secondary forest clearing e.g. for new roads, urban expansion to support a growing workforce and indirect economic activities stimulated by mining

([62]) The analysis for bauxite included eight mining sites with the major commodities reported by the data source as 'Aluminium', 'Bauxite', 'Bauxite/Limestone', 'Bauxite/Kaolin'.

([63]) The study does not present for each commodity separately the forest loss induced exclusively by mining in the off-lease areas, but only for the aggregate of all commodities.

zone of the leases. 15% of forest areas within bauxite mining leases were cleared by 2015, and 10% of the forest areas in the buffer zones of the leases, i.e. in the areas impacted by mining.

Figure 38. Contribution of each commodity to the deforestation in the Brazilian Amazon in areas impacted by mining (left) and average forest loss per commodity (right) ([64]), from 2005 to 2015



Source: Background data from (Sonter et al., 2017).

Almost 18% of global forests are designated as protected areas (NYDF Assessment Partners, 2020). Figure 39 shows the global distribution of bauxite mines' location in relation to nature protected areas.

Box 7. Nature protected areas and mining

Compared to other activities, mining activities have a relatively small demand for land, i.e. 0.15% of the total area in 2012 in the EU ([65]). According to a recently developed dataset (Maus *et al.*, 2020), the area used by over 6,000 active mining sites around the globe adds up to about 57,300 km^2 or 0.011% of the total surface area of Earth; land covered by active mining activities in the EU stretches to 0.045% of its land territory ([66]). Mining activities can be perceived as positive since they create income and jobs, and synergies with other manufacturing activities in the region. However, competition for land can also compromise local land's ability to meet different needs such as agricultural production, housing or nature protection. It might also lead to problems for the mining activity itself, which may face difficulties obtaining the Social License to Operate ([67]). Among the three typical land use that can compete with mining (agriculture, human settlements and nature protection) the existence of nature conservation areas is the main factor restricting mining activity (Horváth *et al.*, 2016).

The most important network of protected areas in the EU Member States is the Natura 2000 ([68]) that includes the so-called Special Protection Areas (SPAs) under the Birds Directive([69]), and Sites of Community Importance (SCIs) under the Habitats Directive ([70]), which should derive into Special Areas of Protection (SAPs). Possible restrictions to the development of extractive activities in these areas depend on the level of protection, where permits can be still granted under specific conditions. Besides, the Nationally Designated Protected Areas ([71]) are areas protected by national legislation. If a country has included sites designated under international agreements such as the EU Birds and Habitats Directives, or the Bern or Ramsar Convention in its legislation, the corresponding protected areas, such as the Natura 2000 or Ramsar sites, of this country are classified within this category.

([64]) Areas impacted by mining include the mining leases (on-lease) and their 0–70 km buffers (off-lease).
([65]) https://rmis.jrc.ec.europa.eu/?page=land-use-and-soil-87ab0f
([66]) The mapped mining area in the dataset could be underestimated for countries and commodities poorly reported by the S&P Global database, e.g. the extraction of aggregates is not covered.
([67]) https://rmis.jrc.ec.europa.eu/?page=social-licence-to-operate-b86e6d
([68]) https://ec.europa.eu/environment/nature/natura2000/index_en.htm
([69]) Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds
([70]) Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.
([71]) https://www.eea.europa.eu/data-and-maps/indicators/nationally-designated-protected-areas-1/assessment

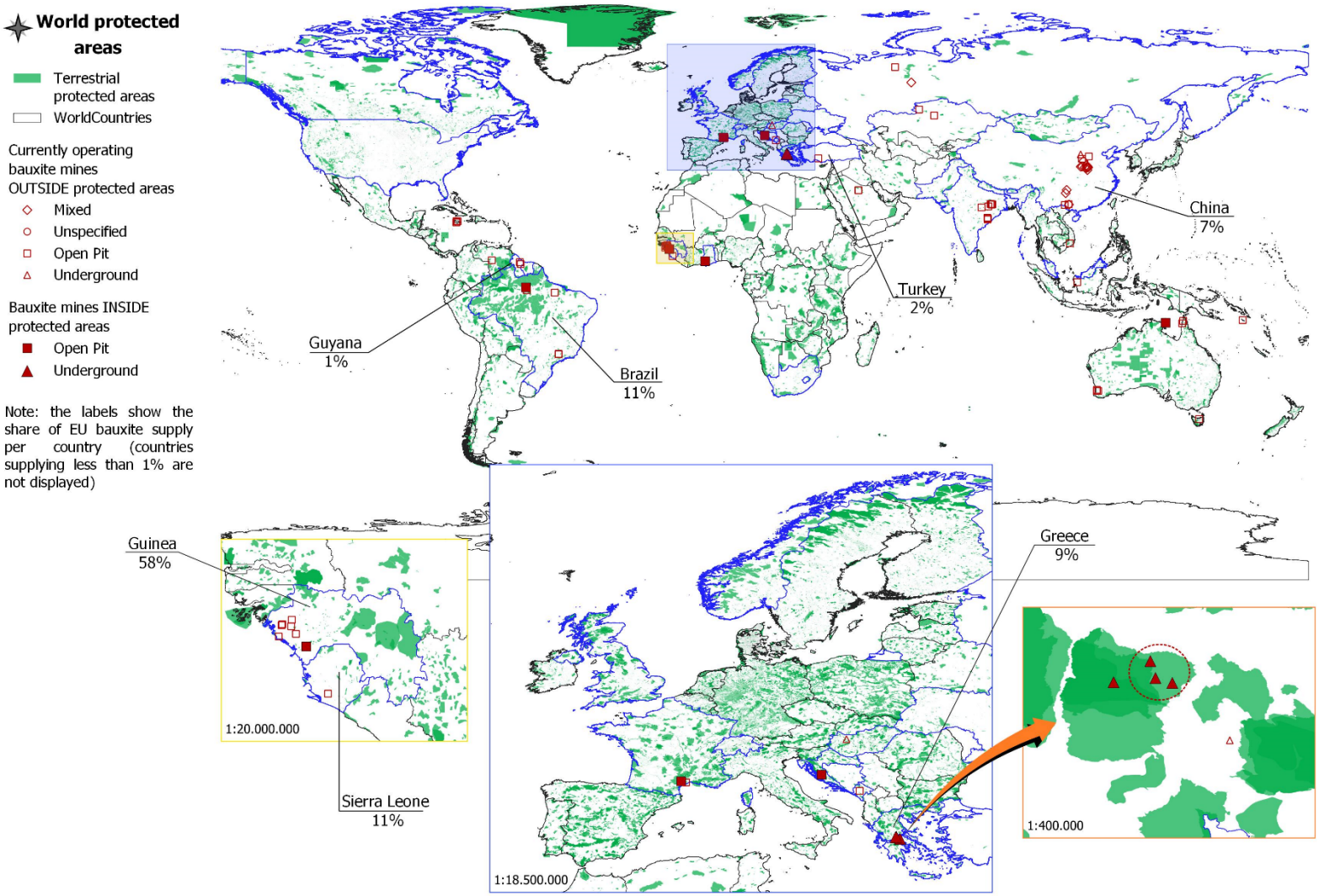
Mining activities can impact nature in different ways: direct removal of vegetation and the associated habitat, impacts associated with the generation of noise and the release of dust and pollutants, which can in turn impact soils, water and the related ecosystems. These impacts can continue in close sites where remediation was not completed or where aftercare environmental management plans are not effective, or in orphan abandoned sites, i.e. Europe has a considerable legacy of abandoned mines; some abandoned mine sites and tailings ponds can still be found even close to residential areas (Dolega et al., 2016).

Outside the EU, although current discussions on raw materials governance focus on active mines, environmental challenges from lack of remediation and legacy mine sites seem to be massive in developing countries (Schueler et al., 2018). Progress toward reducing deforestation from infrastructure and extractive developments while supporting sustainable livelihoods is slow. Instead, forests are under threat by an ever-increasing demand for natural resources, and different land uses, fuelled by global markets, power imbalances, and weak governance (NYDF Assessment Partners, 2020).

The analysis of the location of the operating mine capacity and total industrial resources as shown in Figure 40 versus the nature protected areas worldwide, revealed that the EU bauxite supply originates from countries in which mining is likely to have higher impacts to biodiversity than rest-of-the-world (see Figure 40). A higher share of mine operating capacity (17%) is located within nature protected areas compared to the world average (8%). It is also notable that almost three-quarters of the domestic bauxite capacity is found within nature protected areas, which almost all (98%) are areas designated as Natura 2000's Sites of Community Importance (SCIs) and/or Special Protection Areas (SPAs) and 2% as natural parks. However, EU operating mines, which are located predominantly in the Parnassos/Gkiona cluster in Greece, are mostly underground (96% of capacity, whereas the respective proportion of underworld bauxite mines is only 2% worldwide). Thereby, the area disturbance is typically lower compared to open-pit mining.

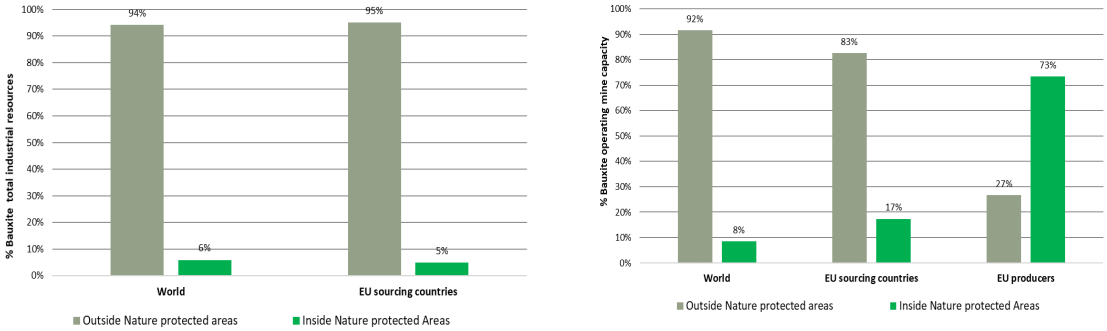
These results should be considered with caution for several reasons. First, the location of the mines in the data sources might be of low accuracy; similarly happens for some protected areas. The mines' site considered is a single point and not the area used for mineral extraction, which would be more reliable for understanding the environmental impacts caused by the mining sector, especially for above-ground extractive activities. Moreover, the interpretation of the implications caused by the overlap between mining activities and protected areas should examine the size of the mine site versus the protected area and the specific location of the mine related to the protected site, i.e. impacts would be different if located in the edge or an important place for the connectivity and survival of species, the invasiveness of the mine practices in place. Finally, adverse impacts extend beyond mining areas due to infrastructure establishment, urban expansion to support a growing workforce, and development of mineral supply chains (Sonter *et al.*, 2017).

Figure 39. Nature protection areas, bauxite mines worldwide and EU sourcing of bauxite



Source: JRC elaboration based on (WDPA, 2020) for world's protected areas; (Reichl and Schatz, 2020) for bauxite production; (Eurostat, 2020b) for imports; (S&P Global, 2020) and various other sources for mines' location and operating status.

Figure 40. Percentage of industrial bauxite resources (incl. reserves) ([72]) (left) and operating bauxite mine capacity ([73]) (right) located within sites with protected conservation status



Source: JRC elaboration based on data from (S&P Global, 2020) for industrial mineral resources.

4.1.4 Country environmental performance

The Environmental Performance Index (EPI) values worldwide are presented in Figure 42, in connection with countries which supply bauxite to the EU.

Box 8. The Environmental Performance Index

Environmental regulation and the surrounding environment's quality are relevant determinants of the potential environmental impact of facilities producing raw materials. It can also determine the risk of possible disruptions in the supply of the material. While stringent regulations can lead to the phase-out of an activity, loose regulations can lead to environmental damages that could, in turn, harm the productive activity itself.

Although not specific for the mining sector, the Environmental Performance Index (EPI) informs about a country's environmental performance: EPI is a distance-to-target index that measures how close a country is to reaching environmental quality targets. Therefore, it is useful to spot countries where the environmental regulation and/or the background environmental conditions are assessed as good and those countries that show room for improvement. EPI's two main components (environmental health and ecosystems vitality) cover a wide diversity of topics (air pollutants exposure, water conditions, biodiversity loss, climate change, etc.)(Wendling *et al.*, 2020)

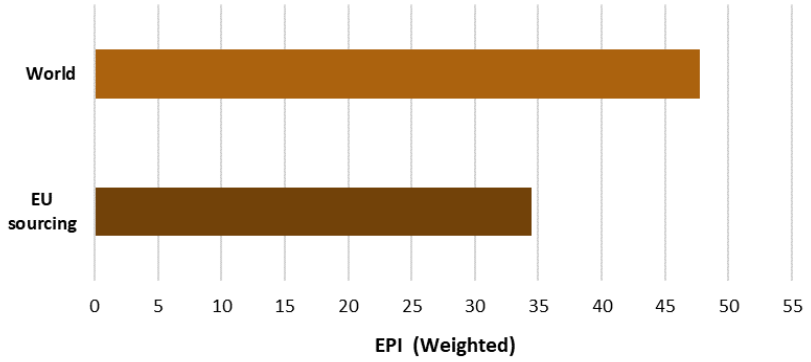
Most bauxite supply to the EU in 2018 originated from Guinea (58%), a country ranging among the lowest EPI values worldwide, i.e. in the 175th rank among the 180 countries covered by the EPI. Guinea's environmental performance has worsened over the past ten years as the EPI score decreased by 4.2 (Wendling et al., 2020). The EPI for Guinea is particularly low in what concerns the environmental health component, partly associated with inferior values in sanitation and drinking water and waste management. Brazil and Sierra Leone follow in bauxite supply to the EU (11% and 10%, respectively). While Brazil shows moderately good EPI values (55 rank, where EPI has increased in the last ten years), Sierra Leone ranks with an EPI even lower than Guinea (177 rank, with a minor increase in the last ten years). Sierra Leone scores even lower than Guinea with regard to waste management. The remaining supply of bauxite comes from Greece, China and Turkey (9%, 7% and 2%, respectively). While Greece falls within the EPI top-25 worldwide, with also an increasing value, Turkey and China ranks lower (99 and 120 rank, yet both with a rising EPI value). Although Greece shows good EPI values, its values are low for ecosystem health, remarkably due to grassland and biodiversity loss.

Looking at the EPI as a weighted average for the group of countries supplying bauxite to the EU in 2018 and the world production (Figure 41), EU suppliers have lower environmental performance than the world supply mix, mainly due to the meagre value for Guinea.

([72]) Industrial resources (including reserves) refer to mines, exploration and mine development projects regardless of activity and development status. They do not comprise resources in not exploited or not explored deposits.

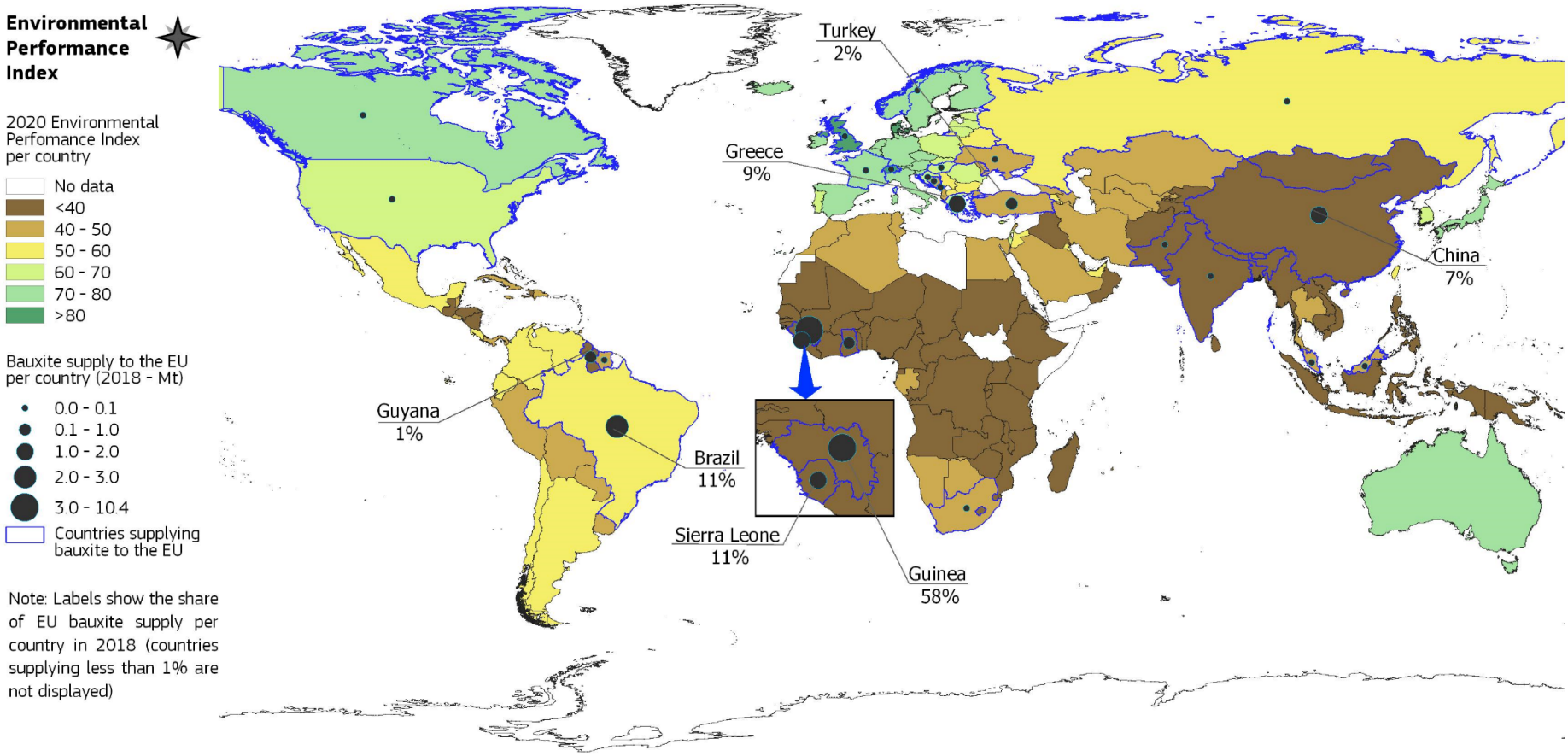
([73]) Annex 1 describes the applied methodology and data sources for calculating mine capacity.

Figure 41. Weighted average Environmental Performance Index (2020 values) for world and EU supply of bauxite in 2018



Source: JRC calculation based on data from (Wendling et al., 2020) for the 2020 Environmental Performance Index.

Figure 42. Environmental Performance Index (2020) and EU sourcing of bauxite (2018)



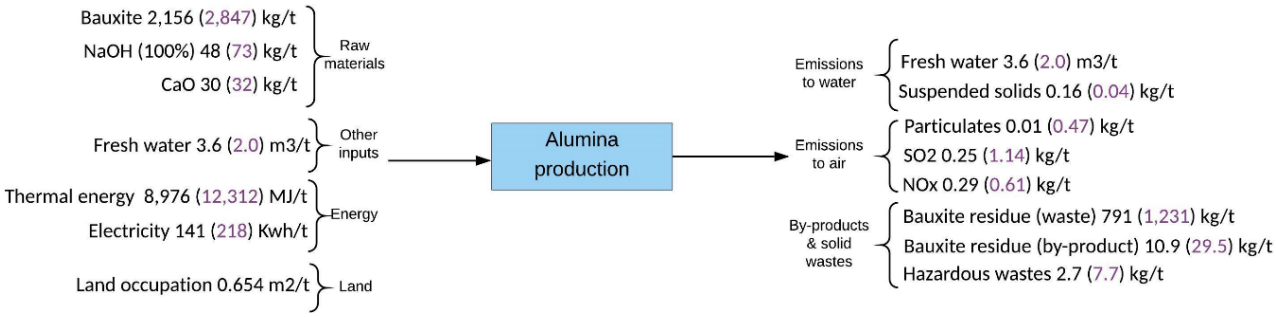
Source: JRC elaboration based on (Wendling et al., 2020) for the 2020 Environmental Performance Index (EPI); (Reichl and Schatz, 2020) for bauxite production; (Eurostat, 2020b) for imports.

4.2 Environmental considerations for alumina production

4.2.1 Emission and consumption levels

Figure 43 compares the average European consumption and emission levels for the production of 1 tonne of alumina with worldwide figures, as modelled by the European Aluminium Association and the International Aluminium Institute

Figure 43. Main consumption and emission levels for the production of one tonne of alumina, Europe ([74]) and world ([75]), 2015 data



Source: Background data in (European Aluminium, 2018b)(IAI, 2017).

4.2.2 Environmental issues in alumina production

The principal environmental matters in alumina production are the following (Hydro, 2012):

- the disposal of the bauxite residue ('red mud'). The bauxite residue (BR) is the most significant waste by volume associated with aluminium production. Its management is one of the most sensitive topics for the green credentials of the aluminium industry. Section 5.3.1 provides information on the conflicts related to BR management at a global level, and Section 6.5.1 describes the disposal practices and recovery solutions to mitigate the social, environmental and economic impacts;
- the energy consumption/energy efficiency;
- the water management;
- the physical footprint of the plant with infrastructure and the red mud disposal area.

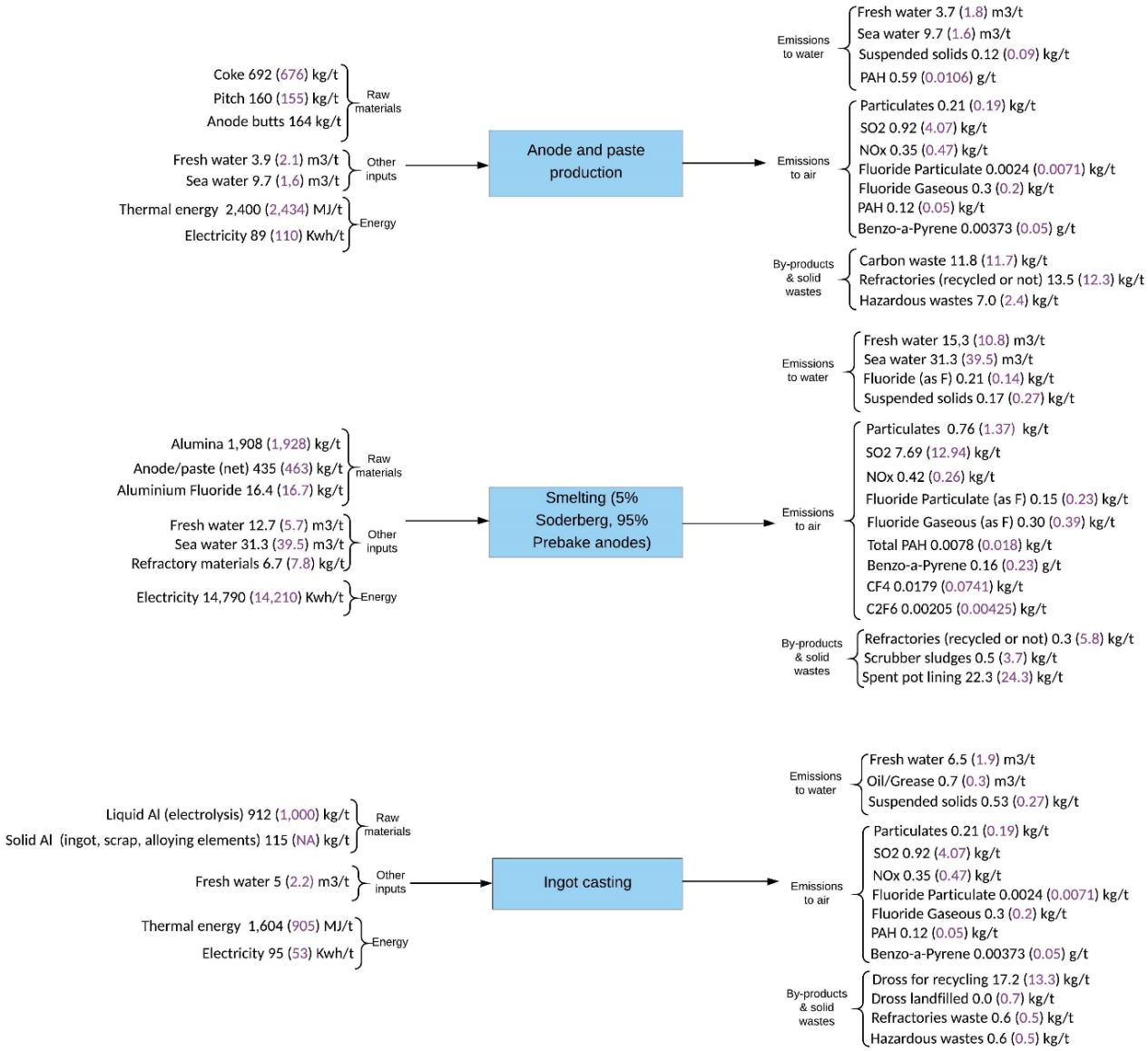
([74]) Europe: EU28+EFTA (Norway, Iceland, Switzerland)
([75]) World data in red

4.3 Environmental considerations for primary aluminium production

4.3.1 Emission and consumption levels

The following figure demonstrates emission and consumption levels of primary aluminium production in Europe compared the world figures for each production process, i.e. anode production, electrolysis and casting.

Figure 44. Main consumption and emission levels by process, for the production of one tonne of anode/paste ([76]), one tonne of liquid aluminium in electrolysis, and one tonne of aluminium ingot, Europe ([77]) and world ([78]), 2015 data

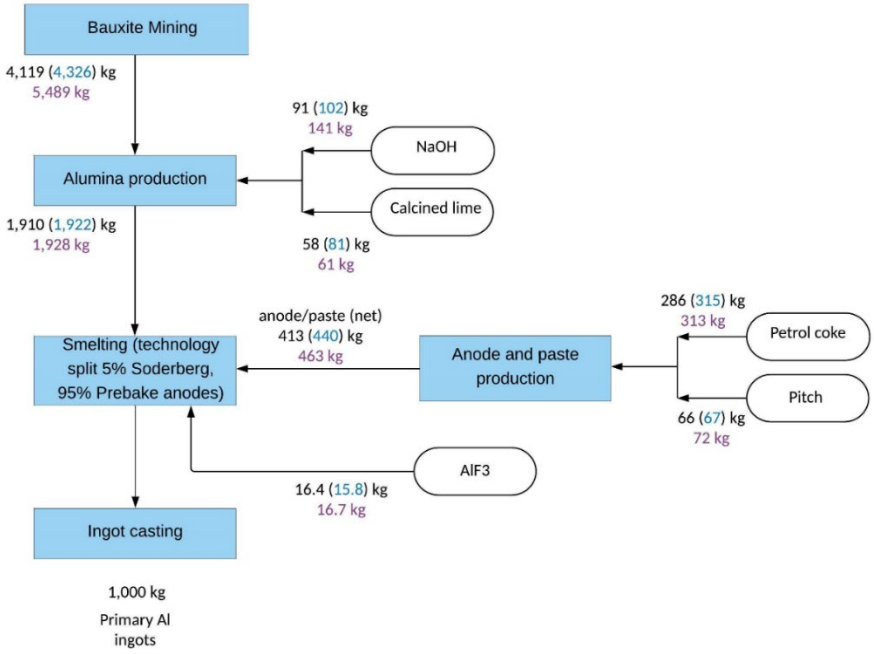


Source: Background data in (European Aluminium, 2018b)(IAI, 2017).

([76]) Mixed paste (5%) and anode (95%).
([77]) Europe: EU28+EFTA (Norway, Iceland, Switzerland).
([78]) World data in colour.

The following figure presents the average consumption of the principal raw materials for producing one tonne of primary aluminium ingot in Europe, as modelled by European Aluminium, compared with the world average. For the primary aluminium production in Europe, 4,326 kg of bauxite, 1,922 kg of alumina and 413 kg anodes are needed to produce 1 tonne of cast primary aluminium.

Figure 45. Mass flow analysis of raw material inputs for the production of one tonne of primary aluminium ingot in Europe ([79]) (2010 and 2015) and worldwide ([80]) (2015)



Source: Background data in (European Aluminium, 2018b)(IAI, 2017).

4.3.2 Environmental issues in primary aluminium production

The most significant environmental challenges related to the production of primary aluminium are listed below (Cusano *et al.*, 2017) (Hydro, 2012).

- Energy production, transmission and consumption (see Section 3.1.1).
- Emissions of greenhouse gases (see Section 3.1.1).
- Emissions of fluorides and polyfluorinated hydrocarbons during electrolysis, emissions of SO_2 from the sulphur content of anodes (mostly from the remaining Søderberg smelters), emissions of dust and emissions of PAH.
- Liquid effluents.
- Solid wastes from the smelting cells (spent pot lining material).

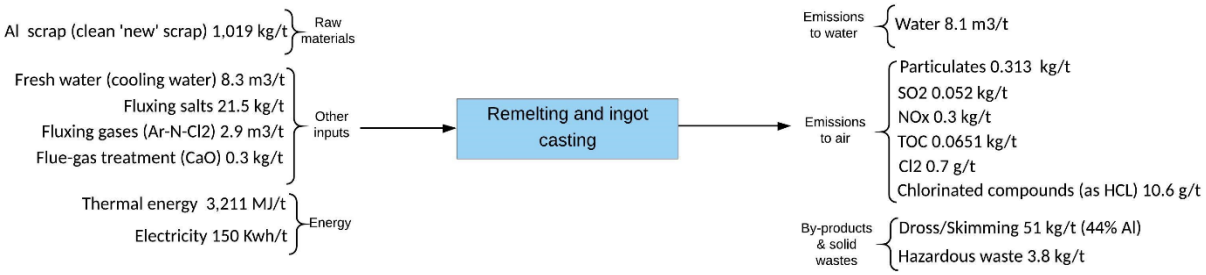
([79]) Europe: EU28+EFTA (Norway, Iceland, Switzerland).
([80]) European production of 2015 in black; European production of 2010 in blue; world production of 2015 in colour.

4.4 Environmental considerations in secondary aluminium production

4.4.1 Emission and consumption levels

The following figure reflects the emission and consumption levels associated with a part of secondary aluminium production([81]) in Europe. No data are available for a comparison with the world average levels.

Figure 46. Main consumption and emission levels for the production of one tonne of secondary aluminium ingot (wrought alloy) from new scrap in a European integrated casthouse ([82]), 2015 data



Source: Background data in (European Aluminium, 2018b).

4.4.2 Environmental issues in secondary aluminium production

Concerning the production of aluminium from secondary sources, the key environmental issues are (Cusano *et al.*, 2017):

— the potential emissions of dust and PCDD/F from poorly operated furnaces and poor combustion. Emissions also depend on the type and the physical state of the secondary raw material, e.g., contamination with acids, oils, organic matter can produce PCDD/F during melting processes; dust is generated mainly during handling and treatment of skimmings/dross (83) and fine dusty scrap and by salt fume;

— the solid wastes, i.e. salt slag, spent furnace linings, and filter dust. Section 6.5.2 deals with the recycling of salt slag.

4.5 Best Available Techniques in accordance with the Industrial Emissions Directive

Best available techniques (BAT) conclusions are the reference for setting permit conditions for installations covered by Chapter II of Directive 2010/75/EU on industrial emissions (IED). Competent authorities should set emission limit values which ensure that, under normal operating conditions, emissions do not exceed the emission levels associated with the best available techniques as laid down in the BAT conclusions.

Best Available Techniques (BAT) reference document, the so-called BREFs, adopted under the Industrial Emissions Directive (IED) 2010/75/EU, for industrial installations in the aluminium value chain are the following:

— the Best Available Techniques (BAT) Reference Document for the Non-Ferrous Metals Industries (NFM BREF) (Cusano *et al.*, 2017). The corresponding "BAT conclusions", i.e. the document containing the parts of a BAT reference document laying down the conclusions on best available techniques, have been published in the Commission Implementing Decision (EU) 2016/1032([84]). The NFM BREF and the BAT Conclusions cover alumina production from bauxite, anode production, production of primary aluminium, production of secondary aluminium, and salt slag recycling. Important issues for the

([81]) Other processes include the recycling of dross/skimmings, recycling of extrusion scrap in integrated casthouses, recycling of various types of scrap in independent remelting installations.

([82]) Integrated remelters as part of rolling plants. For simplification only clean scrap inputs were considered, as feedstock also includes ingots for remelting, alloying elements, and liquid aluminium.

([83]) Dross is generated during aluminum melting and is composed of aluminium oxides and entrapped Al metal. Depending on the scrap input quality and size, between 20 and 100 kg of dross can be produced per tonne of ingot with a metal content varying from 30 to 60% (European Aluminium, 2018c).

([84]) Commission Implementing Decision (EU) 2016/1032 of 13 June 2016 establishing best available techniques (BAT) conclusions for Non-ferrous metals industries. The BAT conclusions on the non-ferrous metal industries concern certain activities specified in Sections 2.1, 2.5 and 6.8 of Annex I to Directive 2010/75/EU.

implementation of Directive 2010/75/EU in the aluminium industry are the emissions to air of dust, mercury, organic compounds (which can result in the formation of PCDD/F), benzo-[a]-pyrene, gaseous fluorides and chlorides, ammonia, phosphine, hydrogen sulphide, nitrogen oxides and sulphur dioxide; diffuse air emissions; emissions to water; resource efficiency; and the prevention of emissions to soil and groundwater;

— the Best Available Techniques (BAT) Reference Document on Surface Treatment Using Organic Solvents (STS), including Preservation of Wood and Wood Products with Chemicals (WPC) (Chronopoulos et al., 2020). The BAT conclusions are published in the Commission Implementing Decision (EU) 2020/2009 ([85]). Industrial activities in the aluminium value chain within the scope of the STS BREF and the BATC is the coating and printing of flat-rolled aluminium sheets, aerosols and collapsible tubes produced by impact extrusion, 2-piece drawn aluminium cans, and packaging closures. Significant issues for the implementation of Directive 2010/75/EU in the surface treatment using organic solvents sector are emissions to air and water as well as energy and water consumption.

Other BAT conclusions and reference documents that are relevant with activities in the value chain of aluminium are:

— the Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries (2018) (MTWR BREF), which covers the management of extractive waste from all onshore extractive industries (Garbarino et al., 2018). This BREF is not subject to Directive 2010/75/EU on Industrial Emissions (IED) but supports the implementation of the Directive on the management of waste from extractive industries (the so-called "Mining Waste Directive", 2006/21/EC). Waste rock from mining activities and bauxite residues are within the scope of the document;

— the Reference Document on Best Available Techniques in the Smitheries and Foundries Industry (2005) (SF BREF) developed under Directive 96/61/EC (IPPC Directive), which covers the production of aluminium castings. The review started in July 2018 (EIPPCB, no date) under the Industrial Emissions Directive (2010/75/EU);

— the Reference Document on Best Available Techniques for the Surface Treatment of Metals and Plastics (2006) (STM BREF) under Directive 96/61/EC (IPPC Directive), which covers aluminium anodising, surface treatment prior to painting, sheet processing for aluminium lithography plates, etc. The review has not started (January 2021) under the Industrial Emissions Directive (2010/75/EU) (EIPPCB, no date).

4.6 Life Cycle Assessment (LCA)

4.6.1 Primary aluminium

The International Aluminium Institute (IAI) collects and publishes Life Cycle Inventory (LCI) data on a long-running basis since 1998, providing a detailed account of the environmental footprint of primary aluminium production worldwide, from the mining of bauxite ore to ingot manufacture. Based on the LCI results, the significance of potential environmental impacts against a defined set of impact categories can be tracked over time. In 2017, the IAI published regionalised LCI datasets for the first time, reviewed by a panel of independent LCA experts (IAI, 2017) (IAI, 2018a).

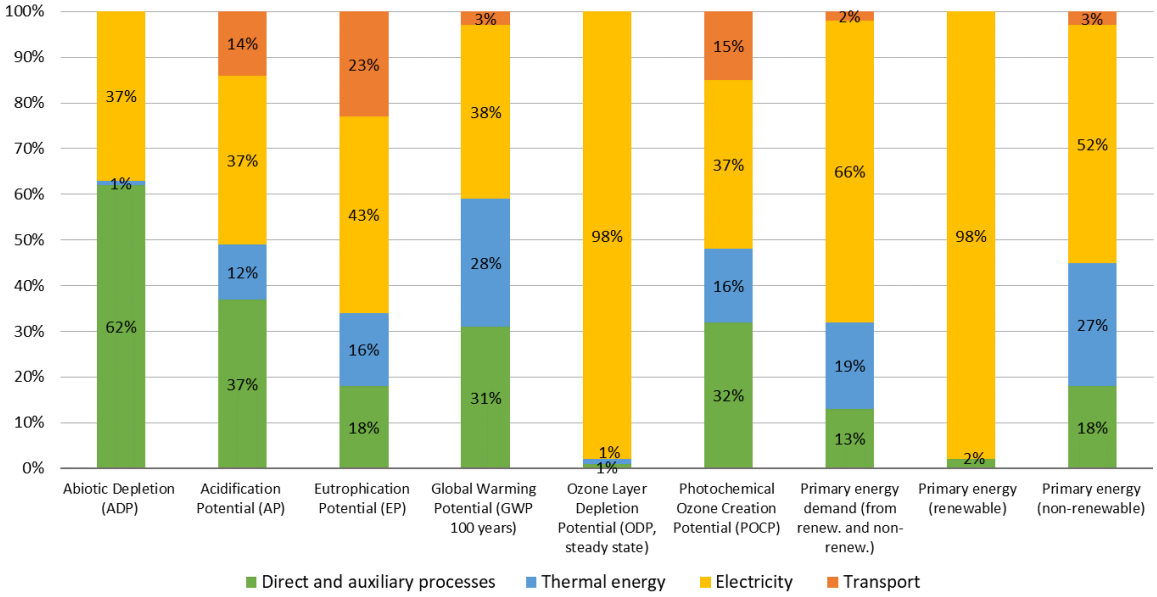
The European Aluminium Association regularly publishes (LCI) data for aluminium production in the EU, UK and EFTA countries (Norway, Switzerland and Iceland), verified by external experts (European Aluminium, 2018b)(European Aluminium, 2018b)(European Aluminium, 2018b)(European Aluminium, 2018b). The latest Environmental Profile report was released in 2018, covering the entire aluminium value chain in Europe, from the metal supply (primary and recycling) to semi-fabrication (rolling, foil and extrusion). Based on 2015 data, the report provides updated LCI datasets for the key process steps, which are essential for evaluating the environmental impacts of aluminium products fabricated in Europe.

The following figure reports the relative contribution of key processes to the main impact categories for primary aluminium consumed in Europe. For the analysis and quantification of the environmental impacts during aluminium production, a cradle-to-gate system was considered. The impacts of electricity production are the

([85]) Commission Implementing Decision (EU) 2020/2009 of 22 June 2020 establishing best available techniques (BAT) conclusions for surface treatment using organic solvents including preservation of wood and wood products with chemicals. The BAT conclusions on the non-ferrous metal industries concern certain activities specified in Sections 6.7, 6.10 and 6.11 of Annex I to Directive 2010/75/EU.

most significant contributor to the environmental impacts of primary aluminium production, except abiotic depletion. Electricity generation and direct and auxiliary ([86]) processes together account for at least 60% of the impacts across all impact category results. For example, these processes contribute about 70% of the Global Warming Potential (GWP) impacts.

Figure 47. Relative contribution to the main environmental impact indicator results by key process type for primary aluminium ingot 'used' in Europe, 2015, cradle-to-gate



Source: Background data in (European Aluminium, 2018b).

Table 2 below compares the results of the environmental performance of primary aluminium production and consumption in Europe. The environmental performance of the primary aluminium produced in Europe improved significantly for most environmental indicators from 2010 to 2015. The substantial decrease of aluminium industry's direct emissions and consumption levels and the considerable increase in hydroelectricity's share in European smelters electricity mix (from about 50% to 70%) explains the robust improvement (European Aluminium, 2018b).

However, the overall environmental impact of primary aluminium consumed in Europe remained relatively stable from 2010 to 2015 for most indicators, balanced by the increased European dependency on primary aluminium imports from regions with a weaker environmental performance in aluminium's production. For instance, the GWP for primary aluminium production in Europe in 2015 decreased by 21% versus 2010, while the GWP of the primary aluminium consumed in Europe decreased only by 1%.

([86]) All ancillary processes and materials used in the aluminium processes. It concerns mainly caustic soda, lime and aluminium fluoride.

Table 2. Comparison of the environmental performance of primary aluminium produced in Europe and primary aluminium consumed ([1]) in Europe, results for one tonne of ingot, cradle-to-gate

Indicators	**'Produced in Europe' (2015 versus 2010) (%)**	**'Used in Europe' (2015 versus 2010) (%)**	**'Produced in Europe' versus 'Used in Europe' (2015) (%)**
Abiotic Depletion (ADP)	-8%	-11%	-50%
Acidification Potential (AP)	-31%	-9%	-87%
Eutrophication Potential (EP)	-21%	+13%	-87%
Global Warming Potential (GWP 100 years)	-21%	-1%	-28%
Ozone Layer Depletion Potential (ODP, steady state) ([2])	-100%	-100%	-21%
Photochemical Ozone Creation Potential (POCP)	-34%	-16%	-64%
Primary energy demand (from renewable and non- renewable)	-8%	-1%	-14%
Primary energy (renewable)	+23%	+3%	-4%
Primary energy (non-renewable)	-18%	-3%	-12%

([1]) The "used in Europe" primary LCI dataset is similar to the "produced in Europe" dataset but considers as well as the primary aluminium which is imported into Europe and which represented 49% of the primary aluminium used in Europe in 2015.

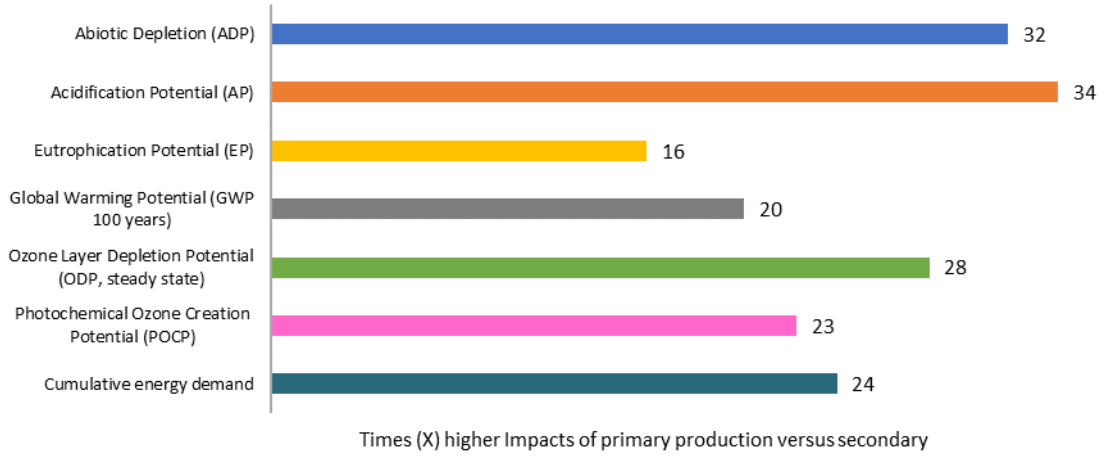
([2]) The decrease of the Ozone Layer Depletion Potential (ODP) in 2015 is due to a change in methodology.

Source: Background data in (European Aluminium, 2018b).

In comparison to other base metals for a range of impact categories, while generally it is not as polluting as copper or nickel production, primary aluminium production shows high impacts per kg of production on many indicators such as climate change, cumulative energy demand, and human toxicity. In contrast, environmental impacts from secondary production are much lower (OECD, 2019).

The following charts display how many times primary aluminium production is more polluting than secondary aluminium production in Europe for a series of impact categories.

Figure 48. Magnitude of environmental impact of primary aluminium production compared to secondary aluminium production, in multiple times, Europe, 2015



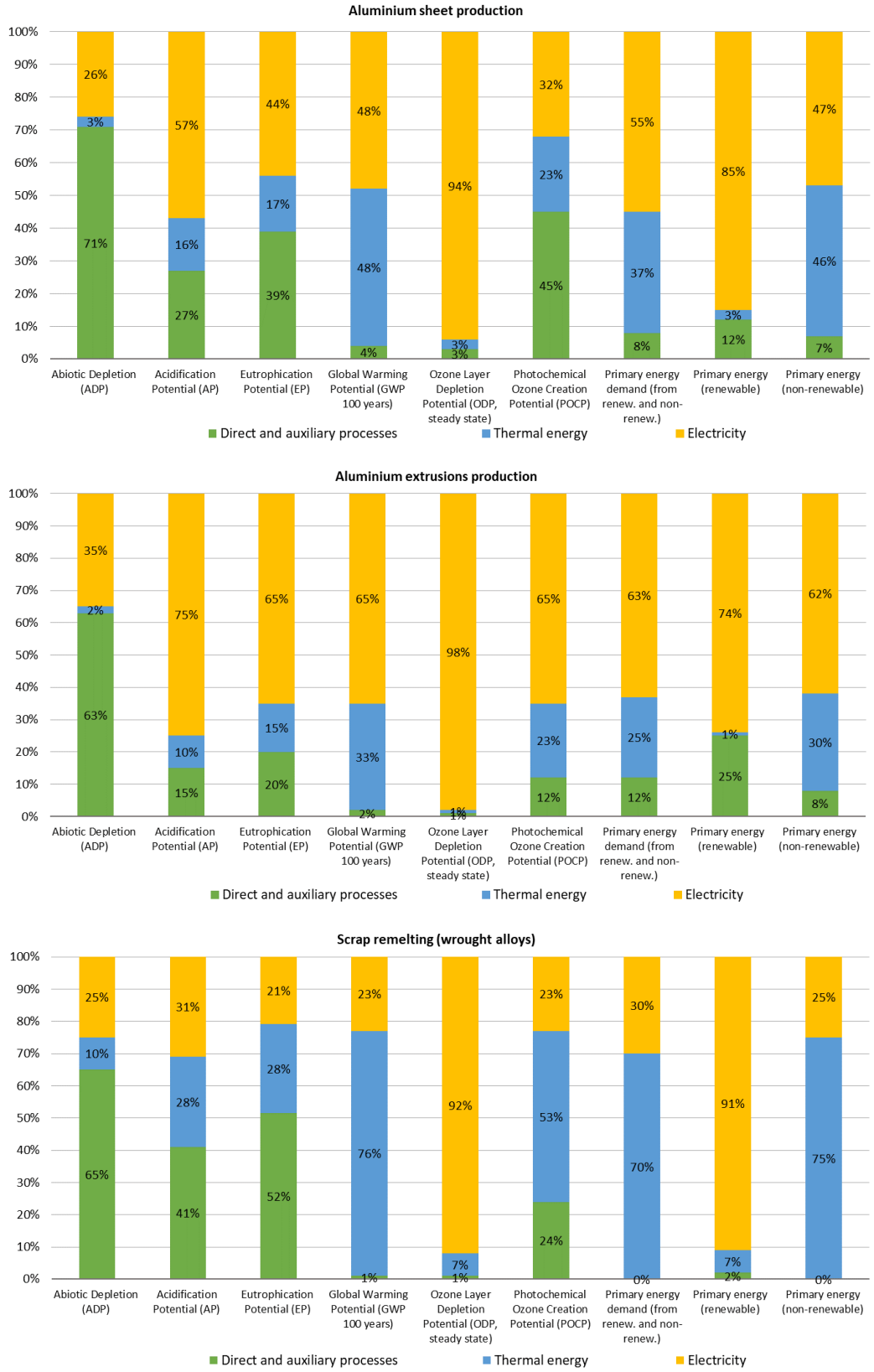
Source: Background data in (European Aluminium, 2018b).

4.6.2 Semi-finished aluminium and recycling

Concerning downstream stages of the value chain and aluminium recycling for the production of wrought alloy ingots,

Figure 49 shows the breakdown per impact category for each environmental indicator. For semifinished products of rolling mills and extrusion plants, electricity production accounts for most of the environmental impacts. In the case of secondary production of wrought alloys, thermal energy accounts for a significant number of impacts. Energy processes (thermal and electrical energy) are responsible for the most significant part of the GWP.

Figure 49. Relative contribution to impact indicator results by key process type for the European production of aluminium sheet (top), extrusions (middle), and secondary ingots, 2015, gate-to-gate



Source: Background data in (European Aluminium, 2018b).

Table 3 demonstrates the significant improvement for most impact categories in the rolling, extrusion, and remelting segments of the European aluminium industry between 2015 and 2010. The positive trend of performance is attributed to the substantial decrease in direct emissions and consumption. For example, the Acidification Potential (AP) decreased by 52%, 37% and 19%, and the GWP by 25%, 11% and 9% for rolling mills, extrusion plants and scrap remelters, respectively. On the other hand, the increase of the Abiotic Depletion Potential (ADP) is largely explained by the strong increase (+326%) of ADP impact of the electricity production in Europe from 2010 to 2015, due to the rising use and the impacts of precious and rare metals in the composition of photovoltaic cells and windmills (European Aluminium, 2018b).

Table 3. Comparison of the environmental performance in 2015 versus 2010 for the production of semi-finished products and secondary wrought alloy ingots ([1]), gate-to-gate

Indicators	**Production of sheets**	**Production of extrusions**	**Secondary production of ingots (new scrap)**
	(2015 versus 2010) (%)		
Abiotic Depletion (ADP)	+162%	+48%	+72%
Acidification Potential (AP)	-52%	-37%	-19%
Eutrophication Potential (EP)	-25%	0%	+3%
Global Warming Potential (GWP 100 years)	-25%	-11%	-9%
Ozone Layer Depletion Potential (ODP, steady state) ([2])	-100%	-100%	-100%
Photochemical Ozone Creation Potential (POCP)	-42%	-32%	-21%
Primary energy demand (from renewable and non-renewable)	-16%	+8%	-4%
Primary energy (renewable)	+110%	+184%	+154%
Primary energy (non-renewable)	-28%	-11%	-9%

([1]) Integrated cast houses in rolling plants using clean process scrap.
([2]) The decrease of the Ozone Layer Depletion Potential (ODP) in 2015 is due to a change in methodology.

Source: Background data in (European Aluminium, 2018b).

In the context of the Environmental Footprint (EF) pilot phase ([87]), Product Environmental Footprint Category Rules (PEFCRs) are developed for metal sheets made of aluminium (among other metals) (Eurometaux, 2019). The PEFCRs are applicable to the applications of aluminium sheet in buildings and appliances. They provide a set of product category-specific rules on how to measure the life cycle environmental performance of the products in scope, ensuring that all Product Environmental Footprints (PEFs) for metal sheets complying with these specific rules are derived, verified and presented in a harmonised way. The EF compliant datasets are available online through the European Commission's EF node in the European Platform on Life Cycle Assessment (EPLCA) ([88]).

([87]) https://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm
([88]) https://eplca.jrc.ec.europa.eu/index.html

Box 9. The Product Environmental Footprint

The Product Environmental Footprint (PEF) is a life cycle assessment (LCA) based method to quantify the environmental impacts of products (goods or services). It builds on existing approaches and international standards. The overarching purpose of PEF information is to enable the reduction of the environmental impacts of goods and services, taking into account supply chain activities (from the extraction of raw materials, through production and use, to final waste management). This purpose is achieved by providing detailed requirements for modelling the environmental impacts of the flows of material/energy and the emissions and waste streams associated with a product throughout its life cycle.

The rules provided in the PEF method enable to conduct PEF studies that are more reproducible, comparable and verifiable, compared to general LCA applications. However, full comparability is only possible if the results are based on the same Product Environmental Footprint Category Rules (PEFCR). The development of PEFCRs complements and further specifies the requirements for PEF studies (Zampori and Pant, 2019).

4.7 Protection of health and environment from chemical substances

Minor environmental and health issues are identified for the aluminium value chain in the context of the implementation of Regulation (EC) 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). Regulation (EC) 1272/2008, on classification, labelling and packaging (CLP) of substances and mixtures, classifies only aluminium powder products as shown in the following table, and some aluminium-containing chemicals (e.g., aluminium chloride, aluminium alkyls) (ECHA, 2020).

Table 4. List of harmonised classification and labelling of aluminium as a hazardous substance

International Chemical Identification	**Classification**	
	Hazard Class and Category Code(s)	Hazard statement
Aluminium powder (pyrophoric)	Water-reactive, category 2 Pyrophoric solids, category 1	H261: In contact with water releases flammable gases H250: Catches fire spontaneously if exposed to air
Aluminium powder (stabilised)	Water-reactive, category 2 Flammable solids, category 3	H261: In contact with water releases flammable gases H228: Flammable Solid

Source: Regulation (EC) 1272/2008; (ECHA, 2020).

5 Social sustainability aspects and governance

5.1 Governance and social risks in producing countries and EU suppliers

This section presents and discusses social considerations related to the production of bauxite and aluminium. The first part of this section focuses on bauxite and presents a series of country-based indicators and indexes for relevant bauxite producers and suppliers to the EU. The second part of this section focuses on the aluminium industry and presents available data on occupational safety and other social aspects, mainly using industry association data sources.

5.1.1 Bauxite

Australia, China and Guinea are the top three producing bauxite countries globally (see Figure 5). Concerning the level of governance in bauxite supplier countries, Guinea is the leading supplier for the EU, providing 58% of the EU sourcing in 2018. Governance is extremely weak in this country, as shown in Table 5. Except for the indicator "voice and accountability", the percentile ranks for the other governance indicators are in the lowest quartile. Sierra Leone, which supplies 11% of the EU sourcing of bauxite, has low governance, especially for government effectiveness and regulatory quality.

Box 10. Worldwide Governance Indicators

The level of governance of a country, as measured by the Worldwide Governance Indicators (WGI) (Kaufmann *et al.*, 2010) "*consists of the traditions and institutions by which authority in a country is exercised*"([89]). This concept encompasses various aspects, including the level of corruption in a country, the government's capacity to formulate and implement sound policies effectively, etc. The WGI are commonly accepted as a way to understand the level of country governance. Even if they are not specific for the extractive industry, they have been used as one of the components to assess the supply risk in the methodology for assessing Critical Raw Materials for the EU (Blengini *et al.*, 2017) and in several other similar criticality assessments.

The World Governance Indicators are based on stakeholders' perception in industrial and developing countries. They cover six dimensions: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, and corruption control.

Table 5. Percentile ranks of Worldwide Governance Indicators 2019 in countries supplying bauxite (higher values indicate better performance)

	Voice and Accountability	**Political Stability and Absence of Violence and Terrorism**	**Government Effectiveness**	**Regulatory Quality**	**Rule of Law**	**Control of Corruption**
Australia	93.1	88.6	92.8	98.6	93.3	94.2
Brazil	58.6	24.8	43.8	48.1	47.6	42.3
China	6.4	38.1	71.6	42.8	45.2	43.3
Greece	77.3	57.1	66.8	70.7	60.6	56.3
Guinea	26.1	17.6	21.2	21.2	9.1	18.3
India	57.6	21.4	59.6	48.6	52.4	47.6
Indonesia	52.7	28.1	60.1	51.4	42.3	38.0
Jamaica	68.5	59.5	70.7	62.0	44.2	54.3
Kazakhstan	14.8	45.7	57.7	61.1	36.1	43.8
Russian Federation	18.2	25.7	58.2	36.1	25.0	21.6
Sierra Leone	41.4	44.3	12.5	17.3	22.6	38.5

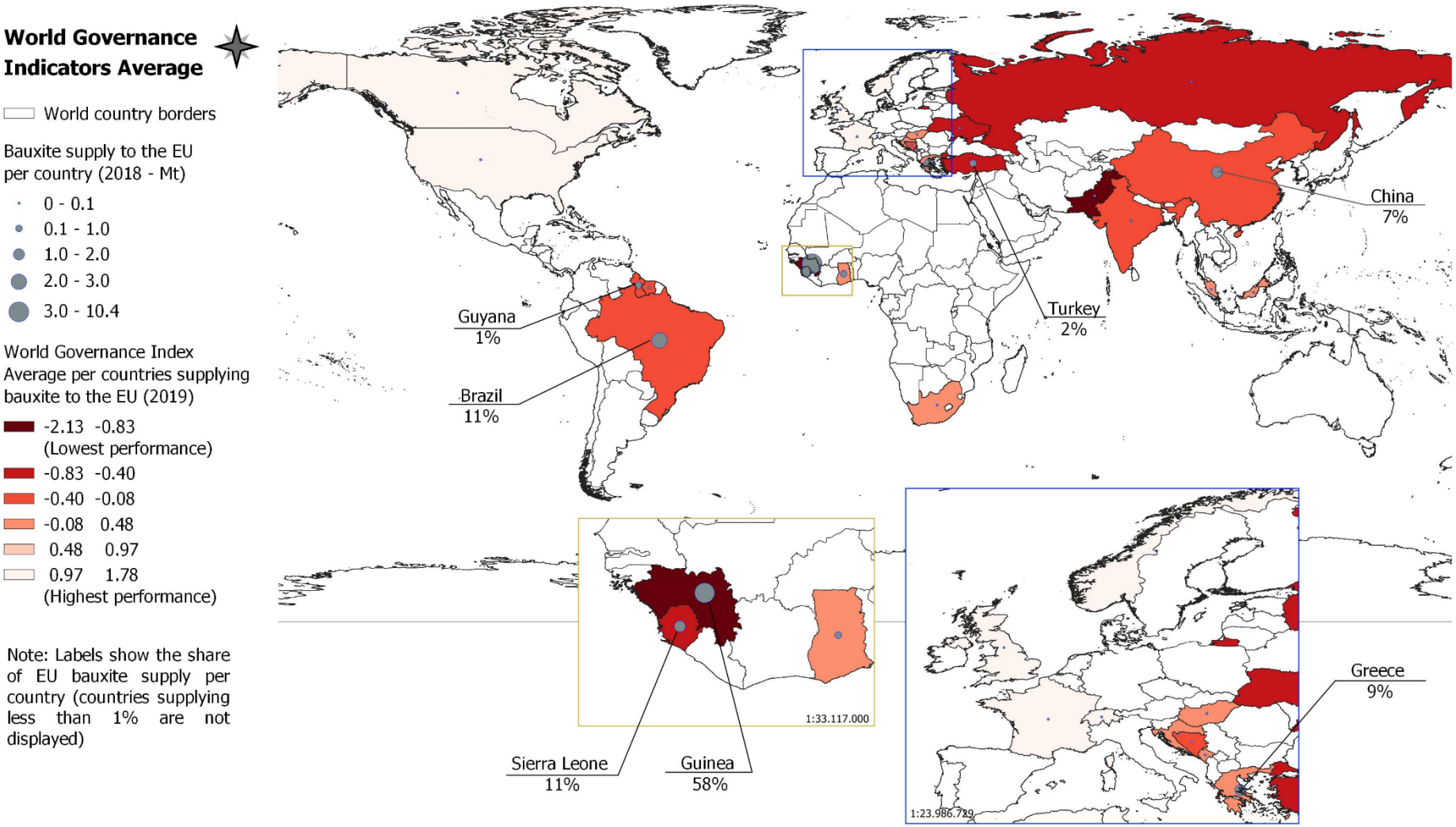
Colour code for the table:

Lowest performance				Highest performance

([89]) http://info.worldbank.org/governance/wgi/

The map in Figure 50 shows the level of governance (expressed as an average of the WGIs) and data on bauxite supply worldwide. Noticeably, Guinea and Sierra Leone have the highest share of production and low levels of governance.

Figure 50. World Governance Index (WGI) for countries supplying bauxite to the EU



Source: JRC elaboration

A more specific indicator used to understand governance in the extractive sector is the Resource Governance Index (RGI) (NRGI, 2017). This indicator provides a more meaningful insight into understanding the social conditions in the sector of bauxite mining. Still, data availability for the mining sector is limited to a set of thirty-eight countries (other data refer to the oil and gas extractive sector).

Box 11. The Resource Governance Index

The Resource Governance Index (RGI) measures the quality of extractive sector governance in resource-rich countries around the world. The RGI defines resource governance as the rules, disclosures, oversight procedures and enabling environment that allow citizens to hold their government to account for managing their extractive resource wealth. It evaluates how resource-producing countries govern their oil, gas and mining sectors, in particular from the perspective of transparency and accountability. The RGI consists of three components: value realisation, revenue management and enabling environment, which in turn consist of 14 subcomponents, 51 indicators and 133 questions.

https://resourcegovernanceindex.org/

Additional social indicators are proposed in Table 6 to indicate specific social conditions that could imply a risk of social impacts in the bauxite mining sector. These regard the risk of conflicts, the level of country development and the incidence of child labour and forced labour, at the country level.

Guinea and Sierra Leone have the lowest values for the Human Development Index and Fragile State Index, which measures socio-economic vulnerability and risk and state capacity to respond to pressures. According to ILO estimates([90]), child labour is also spread in these countries, with 25% (Guinea) and 37% (Sierra Leone) of children between 5 and 14 years old in employment.

Brazil, an important EU supplier for bauxite and many other materials, shows high conflict risk, as expressed by the Global Peace Index and INFORM, as well as India, Turkey and the Russian Federation. The latter also has high values for the Global Slavery Index ([91]), which measure the risk of forced labour.

Table 6. Social indicators in countries supplying bauxite (see methodological notes for data sources)

	Resource Governance Index (mining, 2017)	**Human Development Index (2019)**	**Conflict risk - HH INFORM (2021)**	**Fragile State Index (2020)**	**Global Peace Index (2020)**	**Child labour (%, last available data)**	**Global Slavery Index (2019)**
Australia	71	0.9	0.0	24.1	1.3		1.0
Brazil		0.8	9.0	73.0	2.4	3.4	1.3
China		0.8	6.3	69.9	2.2		2.7
Greece		0.9	0.3	52.2	1.9		2.7
Guinea	38	0.5	4.1	97.2	2.1	24.9	4.0
India		0.7	7.0	75.3	2.6	4.3	2.7
Indonesia	68	0.7	7.0	67.9	1.8		2.7
Jamaica		0.7	0.3	60.0	2.0	2.7	2.0
Kazakhstan		0.8	0.3	59.8	2.0		2.7
Russian Federation		0.8	6.4	72.6	3.1		3.7
Sierra Leone	46	0.4	3.9	84.4	1.8	37.8	2.3
Turkey		0.8	9.0	79.2	3.0		2.7

Colour code for the table:

Lowest performance				Highest performance

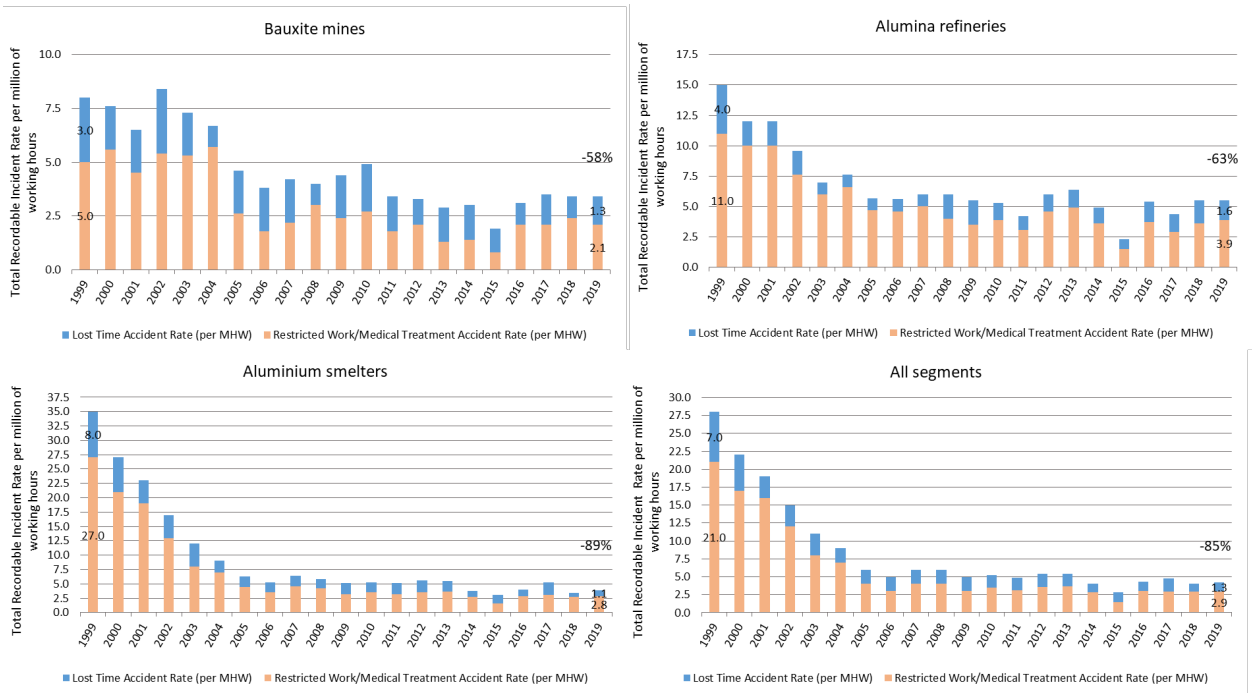
([90]) https://ilostat.ilo.org/topics/child-labour/
([91]) https://www.globalslaveryindex.org/

5.1.2 Aluminium

5.1.2.1 Occupational Health and Safety in the aluminium industry

The International Aluminium Institute collects annual statistical data on workplace safety in the aluminium industry. The Total Recordable Incident rate (TRI)([92]) shown in Figure 51 below is an indicator representing lost time accidents([93]), restricted work cases([94]), and medical treatment cases([95]) per million hours worked. All industrial segments in the data coverage have significantly improved safety performance since 1999, with the most substantial reduction in primary aluminium smelters' accidents rate. However, except for the year 2015 when the best safety performance was recorded for all segments, the TRI indicator has generally plateaued since 2011 in bauxite mining, since 2005 in alumina refineries, and since 2014 in aluminium smelters. Finally, it is noted that accidents in bauxite mines have a higher proportion of Lost Time Accidents in comparison to the other segments.

Figure 51. Workplace accidents in the global aluminium industry([96]) measured by the Total Recordable Incident (TRI) rate per million hours worked



Source: Data from (IAI, 2020j).

The European Aluminium Association publishes safety statistics collected from aluminium companies operating in Europe. As shown in the following figure, the improvement in the industry's performance on Occupational Health and Safety (OHS) is impressive from 1997 to 2009 using the TRI as metrics. The reduction achieved in the TRI indicator from 2012 to 2015, with extended scope in data collection, is 6% (Figure 54). A comparison with the global performance is not possible due to different industry coverage in the two datasets. Figure 54 also demonstrates the declining rate of fatalities.

([92]) Reported as Total Recordable 'Accident' Rate by the data source.

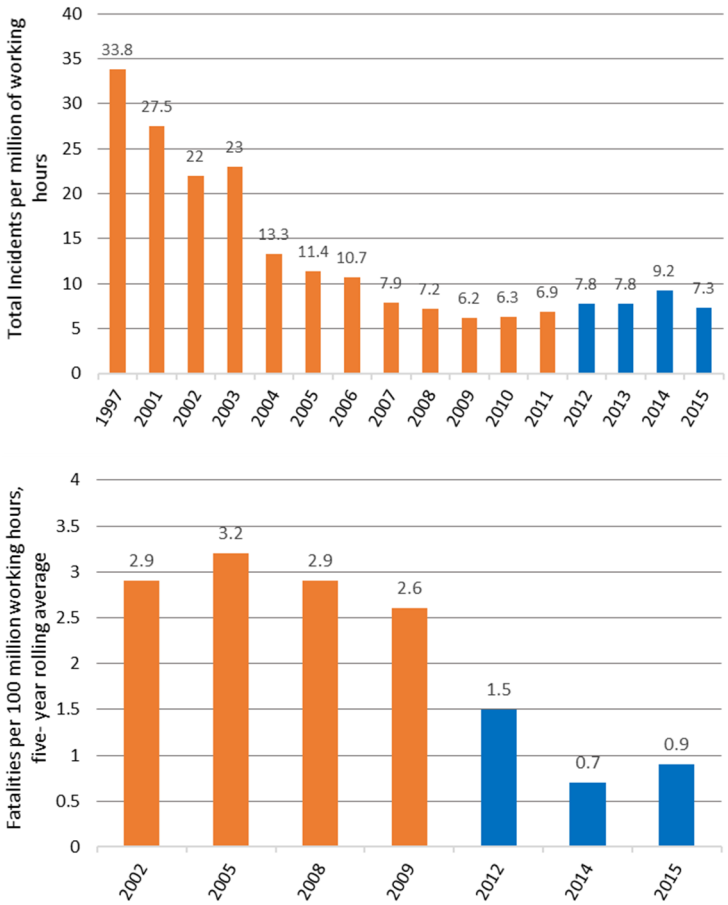
([93]) Lost Time Accident is an accident which results in the injured person being absent for one or more workdays beyond the day of the accident.

([94]) Restricted Work Case is an accident which results in the injured person being assigned to another job, usually of a less demanding physical nature, until recovery allows return to normal activity.

([95]) Medical Treatment is an injury which requires treatment by a doctor or nurse. These injuries are more serious than those requiring simple first-aid treatment.

([96]) The industry coverage is bauxite mining, alumina refining, and primary secondary aluminium production.

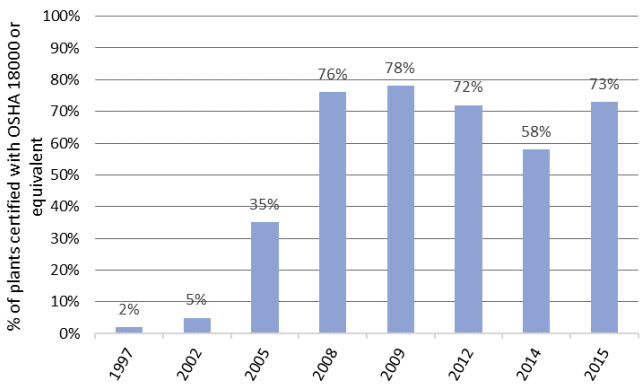
Figure 52. Workplace accidents measured by the Total Recordable Incident rate (TRI) (top) and Fatalities rate (bottom) in the European aluminium industry ([97])



Source: Data from (European Aluminium, 2020b)(European Aluminium, 2017).

Finally, it is worth mentioning that the number of plants that obtained OHS management systems' certification has increased sharply in the period 1997-2008, coinciding with the sharp decrease in workplace incidents and accidents in the same period (Figure 53). The European aluminium industry is committed to reach and sustain zero fatalities and reduce the TRI by 50% between 2012 and 2025 (European Aluminium, 2015).

Figure 53. Percentage of plants in Europe that have declared a certification for OSHA 18000 or equivalent



Source: Data from (European Aluminium, 2017).

([97]) The industry coverage is alumina, primary and secondary aluminium, and semi-finished production. Prior 2012, the refiners' segment of the recycling industry was not integrated into statistics. In addition, from 2013, all fatalities from contractors have been included.

5.1.2.2 Other indicators

In addition to the occupational safety data shown above, the association of the aluminium industry in Europe published additional data related to Corporate Social Responsibility progress in 2015. They refer to the EU28 (thus including the UK) plus EFTA countries (Norway, Iceland, Switzerland and Liechtenstein). The following consideration can be extracted from this data:

Gender equality: The percentage of women employed in the aluminium industry (i.e. total women in industry/total number of employees) was 14% in 2015, and the percentage of women among the leadership team (e.g. plant manager, member of the board) in the European aluminium industry was 16% in 2015 (European Aluminium, 2015).

Skills management and career development: the number of employees in R&D positions increased in the three sectors under consideration in the timeframe 2002-2015: alumina & metal supply (+18%); semi-fabrication (+41%); aluminium industry (+41%). To this increase (in absolute terms) corresponds an increase in the ratio between employees in R&D and the total number of employees, which ranges from 40 to 48% in the three sectors and considering the same timeframe. However, this also depends on the drop in the total number of employees in the sector of alumina and metals supply (-57% in the period 1997-2012) and in the aluminium industry (-12%).

5.2 International initiatives.

5.2.1 Aluminium Stewardship Initiative

The Aluminium Stewardship Initiative (ASI) is a global, multi-stakeholder, non-profit organization dedicated to setting industrial standards and certifications. It gathers together parties involved from the aluminium industry, civil society, research and policy organizations, and industrial users of aluminium products. ASI addresses the aluminium industry's environmental, social and governance sustainability-related risks and opportunities. ASI's objectives include sustainable production methods, material chain-of-custody procedures, recycling, social impacts related to aluminium production, and production standards. The first ASI members got in 2018, and this number continued to grow to reach approximately 100 certifications at the end of 2020 for the whole supply chain (ASI, 2020).

The following table and figure show an overview of certified installations in the upstream aluminium value chain for the most popular ASI standard, the Performance Standard of the Aluminium Stewardship Initiative, published in December 2017 (ASI, 2020). The penetration of the ASI standard is higher in bauxite extraction, as the certified bauxite mines at the end of 2020 represented 30% of the global mine capacity, compared to 18% and 11% for alumina refineries and primary aluminium smelters, respectively.

Table 7. Market uptake of the Performance Standard of the Aluminium Stewardship Initiative at the end of 2020.

	Installations (number)	**Certified Capacity (Mt)**	**Certified capacity (% total capacity)**
Bauxite mines	11	136	30%
Alumina refineries	11	28	18%
Primary aluminium smelters	22	8.5	11%

Source: Background data for certifications in (ASI, 2020); for capacities see Annex 1.

5.2.2 Other industry-led initiatives

The Sustainable Bauxite Mining Guidelines were jointly developed by aluminium associations bodies in Brazil (ABAL) and Australia (AAC). It is intended that these Guidelines are relevant for all bauxite producers globally who strive to operate sustainably, not just those who are seeking to achieve best practice (IAI, 2018b).

The European industry has set voluntary commitments under the Sustainability Roadmap 2025 to achieve responsible production for environmental protection, targeting raw material sourcing, energy consumption, sustainable waste management and water consumption, higher recycling rates etc. Other pillars of the Roadmap

comprise the achievement of aluminium's full potential in innovative applications in mobility, construction and packaging for the transition to a low-carbon economy, as well as higher employee welfare and social engagement (European Aluminium, 2015). Progress towards the voluntary sustainability targets is measured and reported transparently through a set of indicators from data collected regularly. The European Aluminium Association has also connected the Roadmap 2025 with the Sustainable Development Goals (SDGs) making these a strategic issue for the sector (European Aluminium, 2019c).

Finally, three of the global leaders in aluminium supply with activities spanning from bauxite extraction to semi-finished products are among the members of the International Council on Mining & Metals (ICMM), i.e. Rio Tinto, Alcoa and Hydro. The ICMM is an international organization dedicated to a safe, fair and sustainable mining and metals industry by bringing together 27 mining and metals company members and over 35 national, regional and commodities association members. Every company member adheres to ICMM's Mining Principles, which incorporates comprehensive environmental, social and governance requirements, robust site-level validation of performance expectations and credible assurance of corporate sustainability reports (ICMM, no date). Rio Tinto is also a partner in the Mining Association of Canada, which has developed the "Towards Sustainable Mining" program that supports mining companies in managing environmental and social risks.

5.3 Focus on selected socio-economic issues

5.3.1 Environmental conflicts linked to bauxite and aluminium projects

The Environmental Justice Atlas (EJ Atlas) provides an insight into the social acceptance of projects by local communities and the eventual oppositions faced in the development and operation of mining, manufacturing and other activities.

Box 12. The Environmental Justice Atlas (EJ Atlas) ([98])

The Global Atlas of Environmental Justice (EJ Atlas) tool documents and systematises information about conflicts and struggles over the exploitation of natural resources and the related production processes. The online database and interactive map form an international repository on Environmental Justice issues and Ecological Distribution Conflicts. An ecological distribution conflict (EDCs) can be defined as a collective action (such as a writing of petitions, demonstrations, blockades etc.), induced by existing or anticipated environmental pollution or damage to nature affecting communities, which has been caused or will be caused by increases or changes in the social metabolism. The objective is to stop or prevent environmental pollution or damage or to recoup the losses already produced through appeals to civil society, news media and public opinion (national and/or international), public administration (the courts, other government institutions) and business corporations (Temper *et al.*, 2015, 2018).

The Atlas was set up and is managed by the Universitat Autònoma de Barcelona, Spain. It started in 2012 with funding from the seventh framework programme (FP7) for research on 'Science in Society' for the Environmental Justice Organisations, Liabilities and Trade project. For each documented conflict, a set of information is provided, including the commodities produced by a certain economic activity, the conflict's intensity, the related impacts and its duration.

Considering the high and medium intensity conflicts([99]) classified by the EJ Atlas as per January 2021(EJAtlas, 2021) in order to distinguish the most controversial, and started in the last ten years (2010-2020) in order to focus on the most recent, the EJ Atlas reports eight cases worldwide that are related to bauxite/aluminium or energy projects linked to aluminium production. In addition, one severe accident was reported by other sources with a deemed 'high to medium' intensity.These nine conflicts are reported below:

1. In Guinea ([100]), the leading EU supplier of bauxite, protests occurred in the Sangaredi Plateau in the Boké region, where the Bauxite Company of Guinea (CBG) initiated the exploitation of bauxite in 1973. Local communities in the mining areas protested for the negative consequences of the mining activities, including the dynamite explosions occurring in the mines (which for example, caused the collapse of 20 houses in 2015 in the village of Bhoundou Waadhé), the loss of soil fertility, the pollution of rivers and the respiratory problems due to dust exposure. Similar impacts are reported by villages near to the river ports Katougouma and Dapilon used to ship and export bauxite from Guinea ([101]);
2. In Brazil ([102]), Hydro's Alunorte ([103]) is the world's largest alumina refinery and it is located in Bacarena, in the State of Pará. Since the 2000's, water and air pollution affecting health of local communities and workers caused protests and mobilizations. An activist and leader of an environmental organization was killed in 2018. In the same year, following unlicensed emissions of untreated water during severe rains in February, the Brazilian federal court ruled that Alunorte shall restrict operations forcing the

([98]) https://ejatlas.org/
([99]) Socio-environmental conflicts of medium intensity classified by EJ Atlas include street protests and visible mobilisation by local communities. Conflicts of high intensity classified by EJ Atlas comprise those with widespread, mass mobilization, violence, arrests, etc.
([100]) https://ejatlas.org/conflict/bauxite-mining-boke-guinea.
([101]) https://ejatlas.org/conflict/exportation-to-china-of-bauxite-from-katougouma-and-dapilon-ports-societe-miniere-de-boke-guinea.
([102]) https://ejatlas.org/conflict/hydro-alunorte-alumina-refinery-in-barcarena-para-brazil
([103]) The case is included in the list. even though it is reported by EJ Atlas that it started before 2010, in order to account for the severe escalation in 2018.

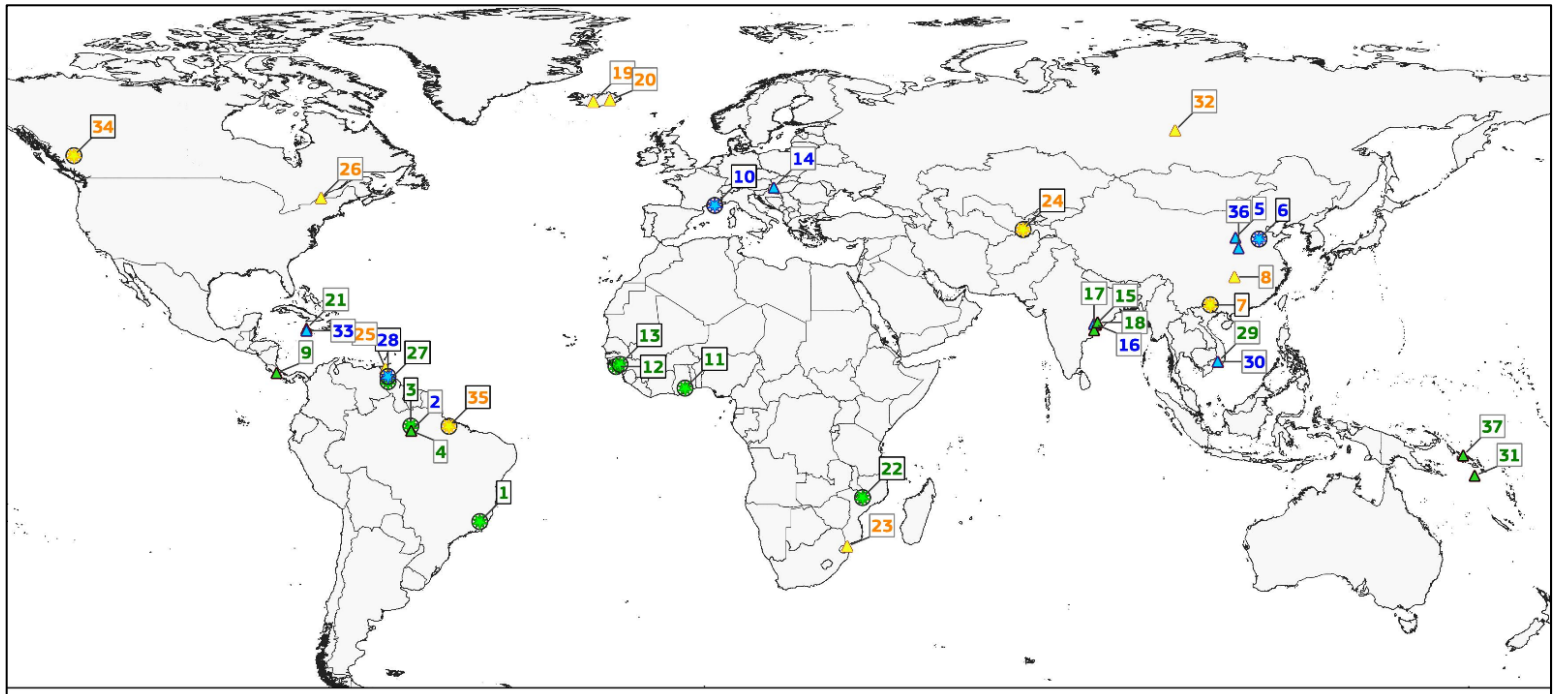
company to slash output by half at the refinery. In May 2019, the production embargo was lifted and operations resumed after the integrity of bauxite residues' disposal area was verified([104]);

3. In Venezuela ([105]), protests occurred against the mining project "Arco Minero del Orinoco" in the state of Bolívar, which is deemed to affect indigenous populations and protected areas. This massive mining project, which would occupy 111,000 km^2, would permit the extraction of bauxite and other minerals;
4. In Mozambique ([106]), mobilizations occurred against the Mozal aluminium smelter, situated in the outskirts of Mozambique's capital, Maputo. The plant, mostly owned by BHP Billiton, is accused of consuming a large part of the country's electricity. Moreover, discharges of pollutants due to the filters' malfunctioning occurred in 2010, affecting a densely populated area;
5. In Tajikistan ([107]), the Tajik Aluminium Company (TALCO) is the largest aluminium producer in Central Asia. It is located close to the border with the Uzbekistan Surkhandarya region, whose population was affected by air emissions such as sulphur dioxide and nitrogen oxides emitted from the plant. Moreover, soil pollution and fluorine water contamination are among the causes of protests started in 2010;
6. In India ([108]), popular protests started in 2012 against the mining bauxite project in the Jerrela Hills, inhabited almost exclusively by Adivasi tribes who would be displaced. According to other sources, however, in 2019 the Andhra Pradesh government cancelled the conditional lease granted to the AP Mineral Development Corporation for mining bauxite ore([109]);
7. In China ([110]), local communities started to protest in 2010 against the pollution caused by the Guangxi Xinfa aluminium producer in Jingxi County. Environmental and health impacts are caused by dust pollution, rocky desertification of green mountains, water pollution, soil pollution, flooding, and poor red mud management, which contaminated river and groundwater. The protests were still ongoing in 2019 (last update of the EJ Atlas);
8. In Malawi ([111]), legal battles and local protests started in 2011 against an exploration project in the Mulanje Massif basin, a UNESCO biosphere reserve. The prospective activities regarded bauxite and rare earths. After a temporary court order halting mineral exploration activity that was later lifted, exploration work recommenced.
9. In the Chinese Henan Province, a waste pond dam collapsed on August 8, 2016, releasing 2 million m^3 of bauxite residues and covering two villages with red mud. Four hundred people were evacuated([112]).

The map in Figure 54 shows the location of all conflicts related to bauxite and aluminium and related energy projects (e.g., hydroelectric dams) reported by the Atlas. It also specifies when conflicts are ongoing or old/latent and the corresponding commodity. Annex 3 describes the methodology applied for compiling the environmental conflicts' dataset. Box 13 presents the identified conflicts in the EU territory.

([104]) https://www.reuters.com/article/us-norsk-hydro-brazil/norsk-hydro-to-boost-alumina-output-as-brazil-lifts-restrictions-idUSKCN1SR2IK
([105]) https://ejatlas.org/conflict/las-luchas-contra-el-mega-proyecto-del-arco-minero-del-orinoco
([106]) https://ejatlas.org/conflict/mozal-mozambique
([107]) https://ejatlas.org/conflict/tajik-aluminium-company-talco-and-its-impact-on-neighboorhood-districts-in-uzbekistan
([108]) https://ejatlas.org/conflict/bauxite-mining-in-paderu-visakhapatnam-india
([109]) https://www.business-standard.com/article/pti-stories/ap-govt-cancels-bauxite-mining-lease-in-vizag-119092601485_1.html
([110]) https://ejatlas.org/conflict/thousands-of-villagers-gathered-to-protest-against-the-jingxi-xinfa-aluminum-plant-in-guangxichina
([111]) https://ejatlas.org/conflict/mulanje-massif-rare-earth-mineral-exploration-malawi
([112]) This event is not reported by the EJAtlas (https://aluminiuminsider.com/red-mud-addressing-the-problem/, https://watchers.news/2016/08/16/major-tailings-dam-failure-in-china-s-henan-province/)

Figure 54. Locations of environmental conflicts in the bauxite/aluminium supply chain



Legend

Commodity

- Alumina
- Bauxite
- Primary Al

Conflict status

- Ongoing
- Latent/Historic
- World country borders

Ongoing conflicts

ID	Name
1	Mine development in Zona da Mata/Serra do Brigadeiro (CBA)
3	Mining and deforestation in Oriximina (Vale)
6	Red mud management in Liaocheng (Xinfa Huayu)
7	Emissions from smelter in Jingxi (Guangxi Xinfa)
10	Red mud managemen in Gardanne (Alteo)
11	Mine development in Atewa Forest (China Railway Int)
12	Bauxite transport in Boké (SMB)
13	Mining in the Sangaredi Plateau (Rio Tinto)
22	Mine development in Mulanje Massif (Spring Stone)
24	Emissions from Regar Smelter in Tursunzoda (Talco)
27	Mine development in Arco Minero del Orinoco
28	Emissions from Bauxilum Refinery (CVG)
34	Hydropower plant for Kitimat Smelter at Bulkley-Nechako (Rio Tinto)
35	Hydroelectic dam for Albras Smelter at Tucuruí (Hydro)

Latent and historic conflicts

ID	Name
2	Red mud management in Alunorte refinery, Barcarena (Hydro)
4	Mine development in Jaruti (Alcoa)
5	Red mud management in Lúliang (Feimei)
8	Emissions from smelter in Hunan (Hunan Chuangyuan)
9	Mine development in Valle del General (Alcoa)
14	Red Mud accident in Ajka (MAL)
15	Mine development in Kashipur (Hindalco)
16	New refinery in Kashipur (Hindalco)
17	Mine development in Paderu (Jindal)
18	Mine development in Niyamgiri (Volcan)
19	Hydroelectric dam for Straumsvik smelter (Rio Tinto)

ID	Name
20	Hydroelectric dam at Kárahnjúkar for Fjardaal Smelter (Alcoa)
21	Mine development in Cockpit Country (Noranda Jamaica)
23	Emissions from Mozal Smelter in Maputo (South 32)
25	New smelter in La Brea (Alcoa)
26	Pollution from Massena Smelter at Turtle Cove (Alcoa)
29	Mine development in Tain Rai (Vietnam National Coal)
30	New refinery in Tan Rai (Vietnam National Coal)
31	Pollution incidents from bauxite transport (Bintan)
32	Hydropower plant for Boguchansky smelter at Kodinsk (Rusal)
33	Coal plant for Alpart refinery at Nain (Jiuquan Iron and Steel)
36	Red Mud accident in Wanji Refinery (Xiangjiang Wanji)
37	Mine development in the Wagina Island (Metallica Minerals)

Source: JRC elaboration based on data from the EJ Atlas (see Annex 3 for details on the selection).

Box 13. Environmental conflicts in the EU

— Opposition against a French refinery

In 2014, mobilization and protests started against Altéo's refinery producing speciality alumina products, located in Gardanne in the Bouches-du-Rhône Department of France. In particular, local collectives opposed the authorization to continue the discharge of bauxite residues (red mud) into a submarine canyon in the Mediterranean through pipes situated at 320–330 m in depth that was taking place since 1967. The conflict has arisen and disappeared regularly over the last 40 years. From 1987 to 1996, many decrees and regulations by the French State ruled the conditions under which the Gardanne alumina refinery was authorized to dispose of the bauxite residue in the sea. (Dauvin, 2010) (EJAtlas, 2021) (Rouchier, 2020).

At the end of 2015, the installation was granted a permit to dispose into the sea wastewater originating from red mud treatment for six more years, starting 1st January 2016. The dispute had been intense for most of the year 2016 and is still lasting (at least by the end of 2019) as the local population kept opposing the decision (Rouchier, 2020). In September 2020, the company announced the operation of a new wastewater treatment plant that enabled full compliance with the regulatory requirements for the quality of the effluents before they are discharged into the sea (Alteo, 2020).

— Catastrophic red mud dam failure in Hungary

On 4 October 2010, the red mud reservoir (tailings dam) collapsed at the Hungarian alumina plant in AjKa run by MAL-Magyar Aluminium Ltd., and nearly one million cubic metres of highly alkaline, saline and metal(loid)-rich sludge was released. The red mud flooded several villages, killed ten people, injured almost 150, and polluted vast areas of land of about 1,000 ha in the surrounding environment, as well as surface waters (all life in a nearby river was eliminated). The Ajka red mud disaster (or the Kolontar/Devecser disaster) is considered to be Hungary's worst industrial catastrophe, one of the greatest ecological disasters in Europe, and the most severe accidental load of red mud slurry ever experienced (EJAtlas, 2021) (European Parliament, 2015) (Katai-Urban and Cseplo, 2010).

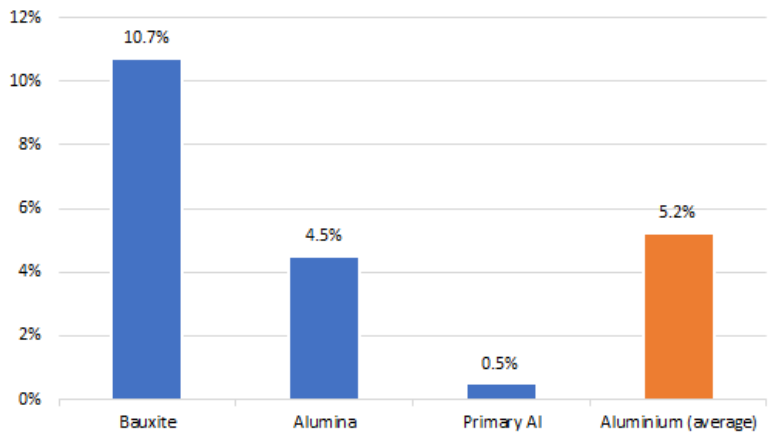
Extensive management efforts in the aftermath of the spill included leachate neutralization and red mud recovery from the affected land. Studies in the aftermath of the spill demonstrated that the dominant short-term impacts were salinity stress and the caustic nature of the sludge, and these rapidly passed in the aquatic environment (Mayes et al., 2016). As concerns long-term impacts of the spill on terrestrial and aquatic environments, research suggests a largely positive prognosis but with the need for long-term monitoring of metal(loid) availability in soil and water systems (Mayes et al., 2016) and soil salinisation (Winkler et al., 2018).

Considering all the events reported in the Atlas linked to the supply of aluminium and taking into account the production capacity of the plants involved in these conflicts (bauxite, alumina, and primary aluminium), it is possible to estimate the share of production capacity subject to conflicts, in the various stages of the supply chain(see Annex 3 for the methodological details). As shown in Figure 55, bauxite is the commodity with the highest share of production capacity subject to conflicts. It should be noted, that while the "*EJAtlas dataset is a large convenience sample of recent and previously documented conflicts from an unknown total number of environmental conflicts worldwide"* and therefore statistically not representative globally, the "*EJAtlas dataset represents currently the most extensive global sample available on environmental conflicts*" (Scheidel *et al.*, 2020). Therefore, the comparative results derived from the EJAtlas information are indicative of the features of that sample only and have a certain level of uncertainty depending on the amount of unknown conflict occurring worldwide.

Concerning the typology of conflicts reported by the EJAtlas and other sources, 12 out of 37 are about the exploration and mine development phase. In these cases, the disputes evolved around land use, potential environmental impacts and displacement of population. Bauxite mining and related activities usually take place on, or near, indigenous lands and local communities, and mining frequently requires access to large zones of land and water resources that sustain local communities (IAI, 2018b). Seven of the analysed conflicts are associated with the management of bauxite residues (red mud) and six of them relate to energy production, typically the construction of hydroelectric dams to supply with electricity aluminium smelters (see Figure 56).

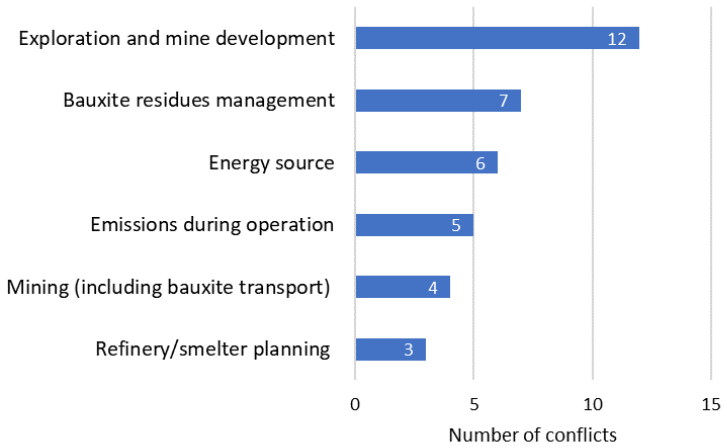
The description of environmental conflicts around the various phases of the aluminium value chain suggests the importance of the social licence to operate into early evaluation stages of potential mining projects, especially in areas where indigenous communities are settled.

Figure 55. Percentage of production capacity subject to reported ongoing conflicts per value chain stage ([113])



Source: JRC elaboration based on (EJAtlas, 2021) (S&P Global, 2020) and other sources (See Annex 3 for details).

Figure 56. Number of reported conflicts by type

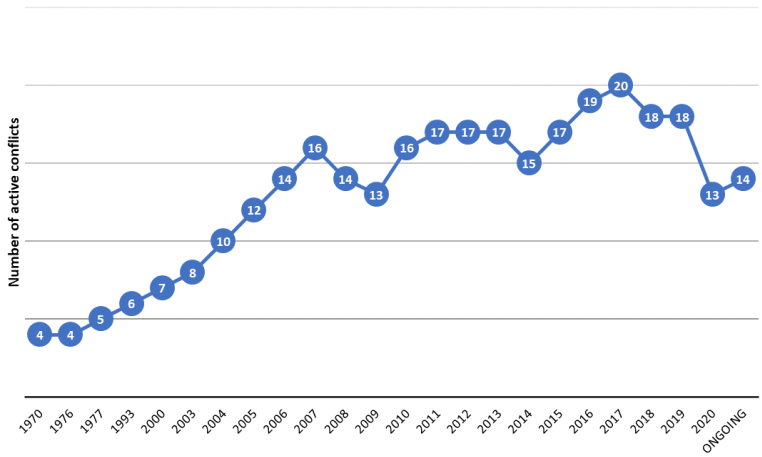


Source: JRC elaboration based on (EJAtlas, 2021) (S&P Global, 2020) and other sources (See Annex 3).

Figure 57 shows the trend in the number of reported conflicts related to bauxite and aluminium since the 70s. The pick in the number of active conflicts was in 2017, and there are currently 14 ongoing events. It should be noticed, however, that past events (i.e. before the development of the Atlas) might be underestimated and that the sample of events described in the Atlas is not statistically representative (due to the unknown number of total conflicts worldwide).

([113]) 'Aluminium (average)' is derived from the average of bauxite, alumina, and primary aluminium capacity subject to conflicts, as a metrics of the whole supply chain of aluminium metal subject to conflicts.

Figure 57. Number of reported active conflicts over time



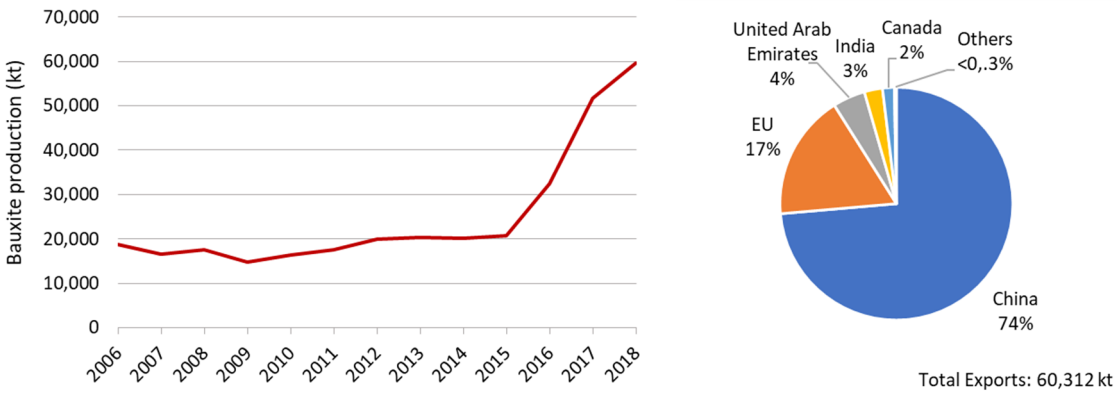
Source: JRC elaboration based on (EJAtlas, 2021) (S&P Global, 2020) and other sources (See Annex 3 for details).

5.3.2 The Guinean bauxite sector

In Guinea, the mining sector has an important role in the national economy, as the mineral rents contribute to 9.8 % of the country's gross domestic product (GDP). Notably, Guinea has the third-highest Mining Contribution Index in the world (ICMM, 2018). This index, developed by the International Council on Mining & Metals (ICMM), indicates the relative importance of mining to the economic life of a country.

Guinea has the largest bauxite reserves in the world corresponding to almost one-quarter of the total (USGS, 2020). It also holds the third position in global bauxite supply with a share of 17% of world production (see Figure 5). Guinea's bauxite sector is booming in recent years, with a two-fold increase in bauxite's output from 2015 to 2018. China's market has absorbed almost entirely the surge of bauxite's production, as shipments to China increased from 0.4 million tonnes in 2015 to 44.4 million tonnes in 2019. In 2019, China was by far the main destination of Guinea's bauxite exports with a share of 74% of the total exported volume from Guinea (Figure 58). The production value in 2018 is estimated at approximately USD 2.6 billion, which equaled about 23% of the country's GDP([114]). Hence, bauxite's role in Guinea's economy and the high annual development rates achieved in the last years([115]) is fundamental.

Figure 58. Evolution of Guinea's bauxite production (left), and export destinations in 2019 (right)



Source: Production data from (Reichl and Schatz, 2020), trade data from (UN Comtrade, 2020).

([114]) Estimation based on an average bauxite price of USD 43 per tonne in 2018, and Guinea's GDP of 10.91 billion in current USD https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=GN [Accessed: 9 April 2021]

([115]) Annual GDP growth: 10.8% (2016), 10.3% (2017), 6.2% (2018), 5.6% (2019) https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?locations=GN

As highlighted in Section 5.1.1, Guinea is the main bauxite supplier for the EU. The analysis of social indicators and governance showed a high risk of child labour, forced labour and conflicts that deserve to be further explored.

The resource governance for mining in Guinea is classified as poor according to the Resource Governance Index ([116]) (RGI) with ''failing'' revenue management, especially for what concerns the "subnational resource revenue sharing" i.e. the distribution of revenues at municipal, district, state or provincial governments level. However, improvements are reported in the interim evaluation 2017-2018 of the RGI (especially in the national budget sub-component contributing to the revenue management component), and the country's RGI is now in a higher performance band, classified as "weak". Government efficiency, the rule of law and control of corruption remain critical aspects in the country (NRGI, 2019). The country is also making meaningful progress in implementing the Extractive Industry Transparency Initiative (EITI) ([117]), joined in 2007.

Some studies analysed the role of bauxite mining corporations in Guinea's political economy over the past decades (Knierzinger, 2014; Diallo, 2019). For instance, the boom of the aluminium industry during the 1960s and 1970s led to the creation of mining towns, where corporations strongly influence infrastructural power (i.e. control of roads, power lines, water pipelines) and the provision of educational and welfare services. Table 8 below resumes some figures on the demography and the employment in Guinea's mining towns. Satellite images in Figure 59 show the large extension of mining operations and their close proximity to urban areas.

Weaknesses of the mining towns development model become visible once the mining activity decreases or stops, as happened in the city of Fria after the 2008 financial crisis and the fall in aluminium prices. The effects of this decline range from increased unemployment and poverty to the closing of facilities and services that the mining company used to provide (Knierzinger, 2016). In Fria and Conakry, the Russian company Rusal suspended its operations in 2012, after workers launched a strike in protest of the management intransigence, leaving about 1,000 permanent employees and 2,000 outsourced workers without payment ([118]).

Table 8. Population growth and employment in mining towns in Guinea

Town	**Population in 1960**	**Population in 2013**	**Number (percentage) of persons employed in the bauxite mining industry**
Fria	5,000	150,000	not available
Kamsar	Less than 1000	140,000	2,500 (1.8%)
Sangaredi	0	65,000	1,300 (2%)

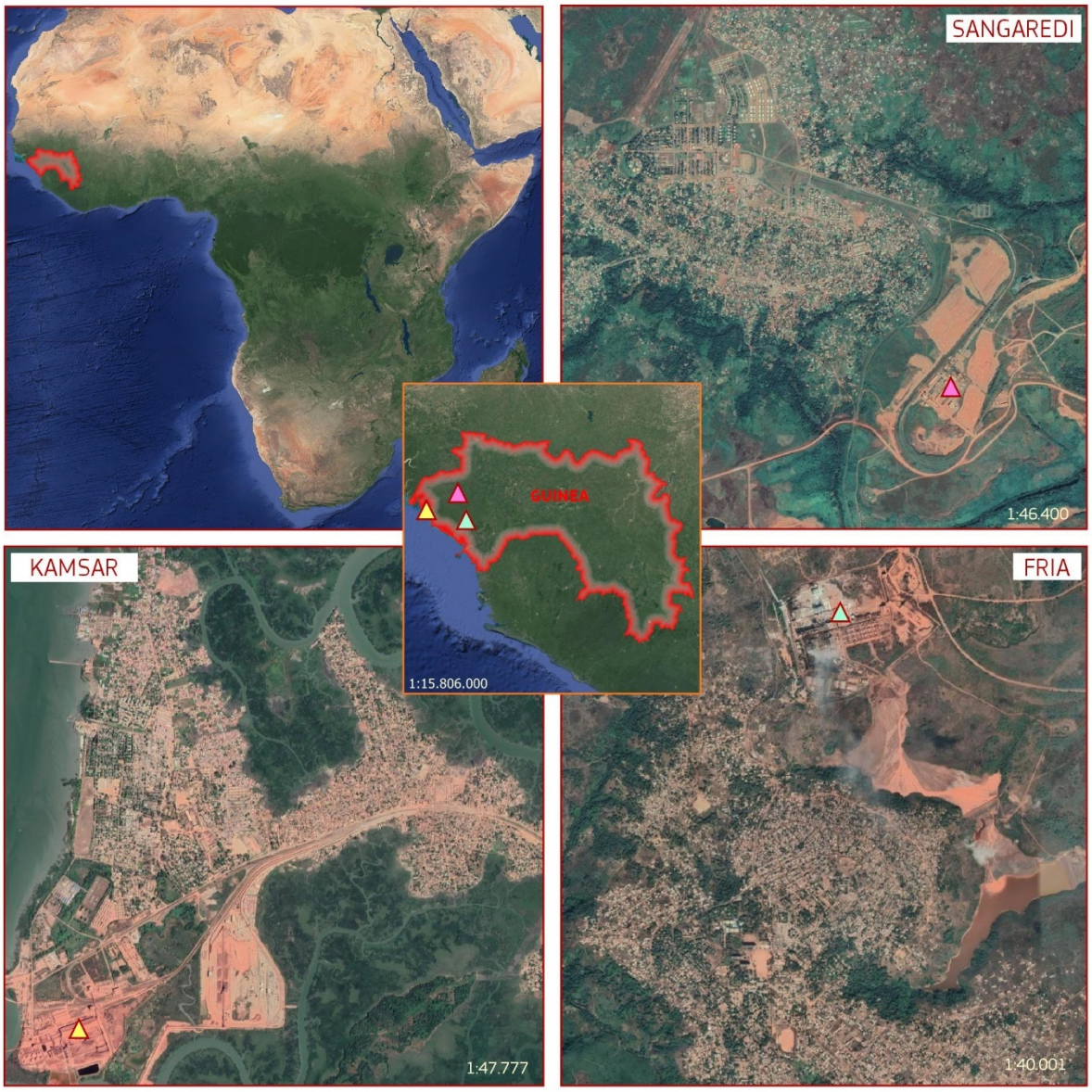
Source: Elaboration of data from (Knierzinger, 2014).

([116]) The Resource Governance Index (RGI) evaluates how resource rich countries govern their oil, gas and mining sectors, in particular from the perspective of transparency and accountability. The RGI consists of three components: value realization, revenue management and enabling environment, which in turn consist of 14 subcomponents, 51 indicators and 133 questions. In the 2017 edition of the RGI, Guinea received a score of 44 out of 100. The 2017 edition assessed the 2015-16 period. The 2019 interim assessment evaluated mining governance in Guinea for 2017-2018. In comparison to the 2017 edition of the RGI, Guinea gains 12 points with its overall score at 56 out of 100, allowing the country to move to a higher performance band, i.e. its performance has improved from 'poor' to 'weak'.

([117]) https://eiti.org/guinea.

([118]) http://www.industriall-union.org/the-drama-of-rusal-friguia-workers-in-guinea.

Figure 59. Mining towns in Guinea ([119])



Source: Basemap credits: Map data ©2021 Google, Imagery ©2021, CNES / Airbus, Maxar Technologies.

A Human Rights Watch (HRW) report describes social impacts on local communities in Guinea's two largest bauxite mining projects (Human Rights Watch, 2018). The report is based on about 300 interviews in mining-affected villages in the Boké region, and interviews with local and national government officials, civil society groups, environmental scientists, public health officials and company representatives. The two projects under investigation are La Société Minière de Boké (SMB), a joint venture that includes a Chinese company that is the largest aluminium producer in the world; and La Compagnie des Bauxites de Guinée (CBG), a company co-owned by the Guinean government and multinational mining companies, including Alcoa and Rio Tinto.

The report describes how the mining activities affect local rural communities in 16 villages, through the expropriation of ancestral farmlands without adequate compensation, or with financial payments that cannot replace the benefits communities derived from land. Moreover, competition for water increased, also due to migration inflows of mining workers. Dust created in the mining operation and the bauxite transport create air contamination, threatening people health and environment. The report also recommends the government develop regulations on uniform compensation process and standards for land acquisitions in the mining sector,

([119]) The triangles highlight the location of the mines.

sanction non-compliant companies, improve transparency, and monitor the quality of the environment in the communities near the mining sites.

The HRW report also hosts the replies of the companies under investigations. Among other arguments, CBG acknowledges that "*individual corporate livelihood compensation programs are insufficient to address the root causes of livelihood issues and poverty in mining concessions communities and the broader Boké region*" and argues to be committed to monitoring environmental impacts. SMB highlights the company's contribution, e.g., in terms of road and bridges construction and establishment of a scholarship for qualified civil servants. These interventions are also described in a report by the International Aluminium Institute (IAI, 2018b).

6 Circular economy aspects

6.1 Facts and figures for aluminium recycling

Aluminium properties do not change during use; therefore, it can be recycled multiple times without losing its original properties. Aluminium has no dissipative uses and it is infinitely recyclable ([120]). As current estimates suggest, the result of aluminium products' recyclability and long lifespan in many applications is that today around three-quarters of all aluminium ever produced (1.5 billion tonnes) is still in use, some having been through countless loops of its lifecycle. In 2019, around 36% of the stock was located in buildings, 25% in electrical cables and machinery and 30% within transport applications (IAI, 2021a). The world's increasing stock-in-use of aluminium constitutes a valuable resource bank of material and embodied energy for use in the future.

The current demand for unwrought aluminium ingots is met by primary (about two-thirds) and secondary sources (one-third) (see Figure 11). Due to the growing demand for aluminium and the long lifetime of many products, the overall consumption of primary metal around the world will continue to be around double that of recycled metal for the predictable future (IAI, 2020a).

According to the International Aluminium Institute's material flow model([121]), scrap availability globally has grown to 33 million tonnes in 2019 from 18 million tonnes in 2009, rising by an average 6% year-over-year. The amount of aluminium produced from old scrap has increased from one million tonnes in 1980 to more than 20 million tonnes in 2019. Currently, recycled aluminium produced from old scrap originates 33% from transport, 26% from packaging, 13% from engineering and cables, and 16% from building applications due to their long-service life (IAI, 2021a).

The production of secondary aluminium is much less demanding in terms of energy, accounting for a consumption per kg of about 5% of the energy needed to produce primary aluminium (Cusano *et al.*, 2017); thereby, GHG emissions are much lower in secondary production (see Figure 16). Likewise, environmental benefits from circularity are seen for each impact category (see Figure 48).

According to European Aluminium, the current status of collection rates achieved in Europe (EU, UK & EFTA) are over 90% for aluminium used in transport and construction and 55% for packaging (European Aluminium, 2020a). According to the latest data announced by Metal Packaging Europe, the overall recycling rate for aluminium beverage cans in Europe reached an all-time record of 76.1% in 2018, rising from 74.5% in 2017. The aluminium beverage cans recycling rates by country range between 99% (Germany) and 98% (Belgium) to 31% (Cyprus) and 33% (Hungary) (Metal Packaging Europe, 2020).

The following table provides an overview of recycling indicators based on the International Aluminium Institute's material flow model and MSA datasets. When it comes to aluminium collection rates at end-of-life, it is deduced that Europe performs better than the global average on the basis of IAI's recent datasets (2018). Contrarywise, the drainage of aluminium scrap collected to export markets (see Section 6.4) in combination with the high demand for aluminium in Europe, does not allow recycling to cover a higher share of consumption (see EOL-RIR in Table 9).

([120]) Assuming a 100% collection and recycling efficiency

([121]) The Alucycle global material flow model is built on the aluminium industry's data from 1962 – 2019 and traces the flow of aluminium along the complete value chain. It covers bauxite mining, alumina refining, aluminium and aluminium ingot production, fabrication (rolling, extrusion and casting), manufacturing (production and assembly of finished products), use and recycling.

Table 9. Recycling rates for aluminium

Data Source	Coverage	Reference year	Recycling Indicators (1)			
			End-of-Life Collection Rate (EOL-CR) (1)	*End-of-Life Recycling Rate (EOL-RR)* (2)	*End-of-Life Recycling Input Rate (EOL-RIR)* (3)	*End-of-Life Circular Material Use (CMU)* (4)
IAI's Alucycle	World	2018	73%	72%	19%	24%
IAI's Alucycle	Europe (5)	2018	79%	69%	20%	36%
MSA study	EU28	2013	69%	51%	12%	35%

(1) The EOL-CR measures the proportion of material at end-of-life that is collected for recycling. It also indicates the amount of aluminium scrap that is diverted from the recycling stream to landfills. Further details are provided in Annex 4.

(2) The EOL-RR refers to the fraction of aluminium in waste flows that is actually recycled at the end of a product's life cycle. It provides a measure of the amount of aluminium scrap recycled domestically as a percentage of end-of-life aluminium available for recycling. Further details are provided in Annex 4.

(3) The EOL-RIR measures the contribution of recycled material to overall demand, i.e. how much of aluminium's input into the production system comes from recycling of "old scrap" (scrap from end-of-life products). The EOL-RIR does not take into account material recovered from "new scrap". Further details are provided in Annex 4.

(4) The EOL-CMU, also known as circularity rate, is defined as the ratio of the circular use of material to the overall material use. The circular use of materials is approximated by the amount of end-of-life waste material recycled in domestic recovery plants minus imported waste destined for recovery plus exported waste destined for recovery abroad. Further details are provided in Annex 4.

(5) Countries covered: EU28, Iceland, Moldova, Montenegro, North Macedonia, Norway, Serbia, Switzerland, Turkey, Ukraine as described in (Bertram *et al.*, 2017).

Source: JRC calculations based on data from (IAI, 2020d)(Passarini et al., 2018).

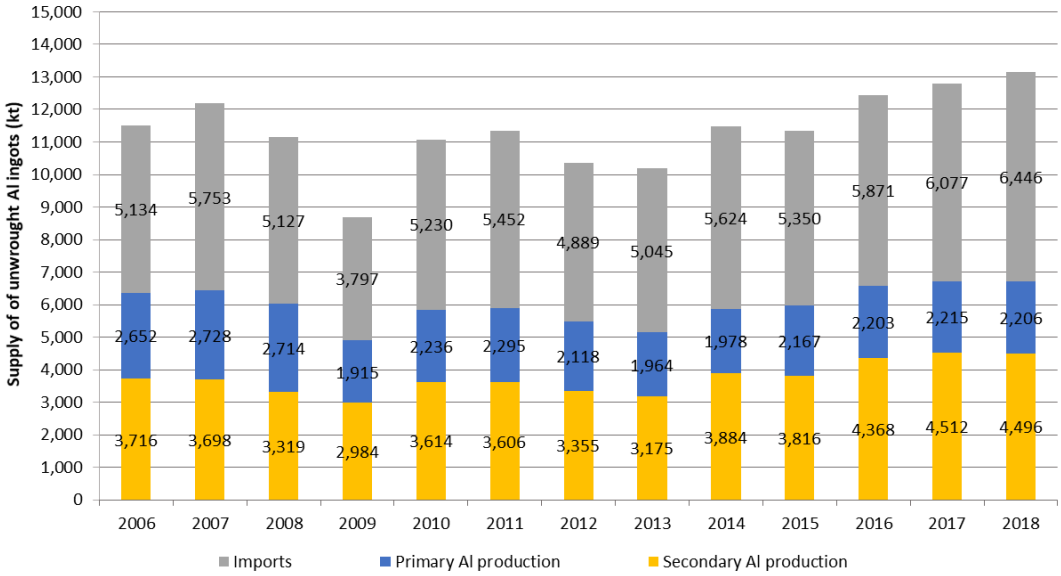
6.2 Contribution of recycling to the security of supply

Statistical data on secondary aluminium production are not publicly available. It is estimated that EU secondary producers shipped 4.5 Mt of ingots in 2018 that is almost equal to the record level of 2017 (Figure 60). In line with data published by the European Aluminium (European Aluminium, 2019a), aluminium produced from scrap in the EU and UK amounted to 4.8 Mt in 2018, 4% lower than in 2017. According to data provided by the International Aluminium Institute, recycling ingot production in Europe ([122]) in 2018 is calculated at 5.3 Mt (from old and new scrap), making up 56% of the total metal production (IAI, 2020d)(Bertram et al., 2017).

Figure 60 below displays the contribution of secondary aluminium production in the total supply of unwrought aluminium in the EU. Unwrought aluminium production required to serve EU demand amounted to just over 13 million tonnes in 2018 of combined primary and secondary aluminium. The estimated output of ingots by EU secondary producers grew significantly at a CAGR of 6.6% from the latest low point in 2009 to 2018, i.e. from 3 Mt to 4.5 Mt. Secondary production covered about one-third (34%), primary production accounted for less than one-fifth (17%), and imports for almost half (49%) of the total EU consumption in aluminium ingots in 2018. The unwrought aluminium produced from secondary sources accounted for two-thirds (67%) of the total aluminium production in the EU.

([122]) Countries covered: EU27, UK, Iceland, Moldova, North Macedonia, Norway, Serbia, Montenegro, Switzerland, Turkey, Ukraine as described in (Bertram et al., 2017).

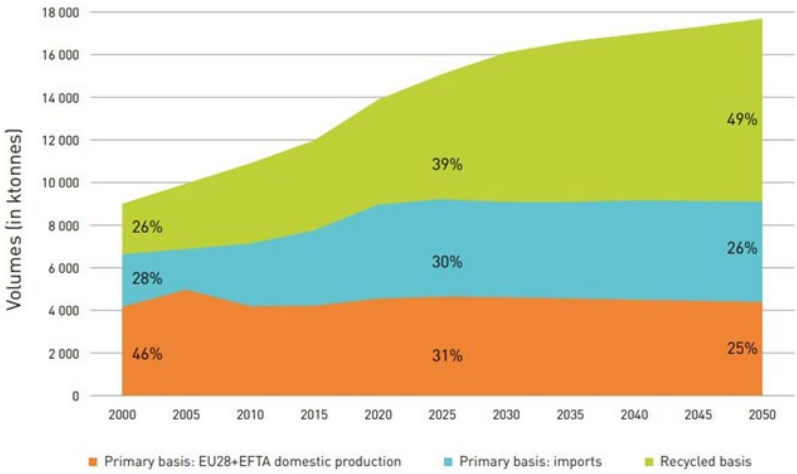
Figure 60. Structure of supply of unwrought aluminium ingots in the EU, 2006-2018 ([123])



Source: JRC elaboration based on background data from (BGS, 2020)(Eurostat, 2020b)(Eurostat Prodcom, 2020).

A European Aluminium Association's report (European Aluminium, 2019d) highlights that the demand for aluminium in Europe by mid-century could be met by almost equal shares of primary (domestic production plus imports) and secondary aluminium through post-consumer recycling, even with strongly growing demand; the expected increase of European demand for aluminium is projected at about 50% (Figure 61). The amount of post-consumer aluminium available for recycling will more than double by 2050, from 3.6 million tonnes per year in 2019, to 6.6 million tonnes in 2030 and to 8.6 million tonnes in 2050 (European Aluminium, 2020a).

Figure 61. Forecast of aluminium supply in Europe (EU+UK+EFTA)



Source: (European Aluminium, 2019d) based on CRU data.

([123]) Data of volume sold (shipments) for the PRC code 24421155 '*Unwrought aluminium alloys in secondary form*' was used in the period 2006-2012. From 2013 to 2018, the production of secondary aluminium ingots was estimated by subtracting the primary aluminium production reported by the BGS from the total unwrought aluminium ingot shipments reported by Prodcom. A similar estimation is not possible for 2019 as the primary aluminium output is not published yet (January 2021) by open sources. The secondary ingot production does not reflect the aluminium recovery from old scrap as it may include new scrap (toll-treated) and primary aluminium used as additional feedstock. In addition, the unwrought aluminium ingot shipments used to estimate secondary ingot output may not include production by integrated casthouses at semis plants, where old scrap may be recycled and ingots are consumed internally.

6.3 Contribution of aluminium recycling to GHG emission mitigation and increasing aluminium's circularity potential

As it has been already discussed in Section 3.1.1, energy and carbon footprint savings are substantial in secondary aluminium production, as remelting scrap metal requires just 5% of the energy needed for primary production. To put into perspective the beneficial impact, the total amount of old scrap recycled in 2019 worldwide represents a total GHG emissions annual saving of about 330 million tonnes([124]) of CO_2eq. If the aluminium sector was a country in terms of its emissions, the amount of annual GHG savings would be equivalent to the annual GHG emissions of a country having a population similar to Poland([125]). In case the total (old+new) scrap volume([126]) generated worldwide is accounted for recycling, the annual gains are almost as much as Italy's GHG emissions.

A study by Material Economics (Material Economics, 2018) measured the potential impacts of the circular economy for GHG emissions reduction among the four materials having the most significant emissions (steel, plastics, aluminium and cement). The study concluded that reducing through recycling the amount of primary aluminium required to meet demand, even in market conditions of rapidly growing demand globally up to 2050, is crucial for lowering cumulative emissions from aluminium production, which are what matters most for the climate. Increasing the production of aluminium from secondary sources will also reduce the claim that aluminium makes on clean energy and, thus, reduce the cost and increase the feasibility of industry's decarbonisation. To provide the order of magnitude for the above implication, according to the study's demand growth scenario, the complete decarbonisation of aluminium smelting through low-carbon power would require in 2050 additional zero-carbon electricity that is almost as much as the amount of electricity India uses today (Material Economics, 2018).

In Europe, secondary aluminium from post-consumer recycling could cover half of the demand in 2050 (see Figure 61), compared to 20% in 2018 (see Table 9). In order to capture aluminium's full circularity potential, recycling rates must increase to enable a larger production share from secondary raw materials. In addition to the prevention of CO_2 emissions, the benefits of boosting aluminium's recycling include the reinforcement of Europe's strategic autonomy, as discussed in Section 6.2.

The main challenges to enhance aluminium's circularity can be grouped as follows:

a. Losses of aluminium throughout the use cycle.

Globally, 73% of aluminium from end-of-life products was collected for recycling in 2018, whereas in Europe, the rate is 79% (see Table 9). Despite the higher end-of-life collection rate, 21% of end-of-life aluminium still goes to waste. Securing higher collection rates of aluminium scrap from consumer products – collection from buildings and transport applications is already very high – is needed to counter these losses. Undoubtedly, an improved product design to make disassembly and recycling more straightforward and cost-efficient would increase recycling rates;

b. Indirect 'downcycling' of wrought alloys to aluminium castings and wrought alloy segregation.

Aluminium can be remelted endlessly but a factor that complicates secondary production is that aluminium is predominantly used in alloy form. The presence of alloying elements hinders secondary aluminium production of wrought alloys. Even small deviations in the composition can undermine the quality of the products as aluminium's wrought alloys have very tight specifications to ensure the desired properties. Furthermore, the alloy content in wrought aluminium alloys is much lower compared to casting alloys. Consequently, secondary production is possible when wrought alloys are recycled into less-pure casting alloys, e.g. when rolled and extruded scrap is being mixed with casting scrap, but complicated to impossible when incompatible alloys with product specifications are recycled into wrought alloys. In Europe, alloy to alloy separation of end-of-life aluminium scrap for wrought alloys (rolling and extrusion scrap) has been estimated at 65% (Bertram *et al.*, 2017); the remainder is mixed in unsorted scrap suitable for aluminium castings.

([124]) Based on a substitution of primary aluminium by 20.6 Mt of recycled aluminium worldwide as estimated by the International Aluminium Institute (IAI, 2020d). The carbon footprint values are calculated according to the annual GHG emission per tonne of metal in 2018 reported by (IAI, 2020c), i.e. 16.6 tonnes CO_2 eq/tonne of primary aluminium and 0.5 tonne CO_2 eq/tonne of recycled aluminium providing a GHG saving of 16.1 tonnes/tonne recycled aluminium.

([125]) A yearly GHG emission of 8.7 tonnes per capita in the EU is assumed according to Eurostat https://ec.europa.eu/eurostat/databrowser/view/t2020_rd300/default/table?lang=en

([126]) 33.5 Mt of old+new scrap recycled around the globe in 2019 (IAI, 2020d).

More efficient scrap sorting and pre-treatment technologies applied by waste treatment installations would allow for high-quality and adequately segregated scrap by product/alloy or alloy family. The optimisation of scrap segregation to avoid as much as possible the mixing of different alloys will have the following benefits:

- Increased scrap availability for wrought alloy production;
- Less virgin (primary) aluminium requirement in secondary production for the dilution of dissolved contaminants . Remelters may need up to 25% primary metal ([127]) or low-alloyed scrap to dilute the melt and reach the required chemical composition (Material Economics, 2018).
- Preserving the value of aluminium scrap as unsorted scrap trades at a discount to segregated scrap;
- Low alloy sorting (scrap mixing) has contributed to a surplus of casting scrap in Europe and net exports to other regions (see Section 6.4).

As automakers shift production to electric vehicles, the demand for aluminium castings is expected to decline (Material Economics, 2018); at the same time post-consumer scrap availability will be increasing. In the context of reduced demand for aluminium castings, using wrought alloy scrap in secondary aluminium for castings will no longer be a viable strategy and preventing downcycling will become a compelling need for enhancing aluminium's circularity.

c. Exports of aluminium scrap and the unknown whereabouts of end-of-life (EOL) vehicles.

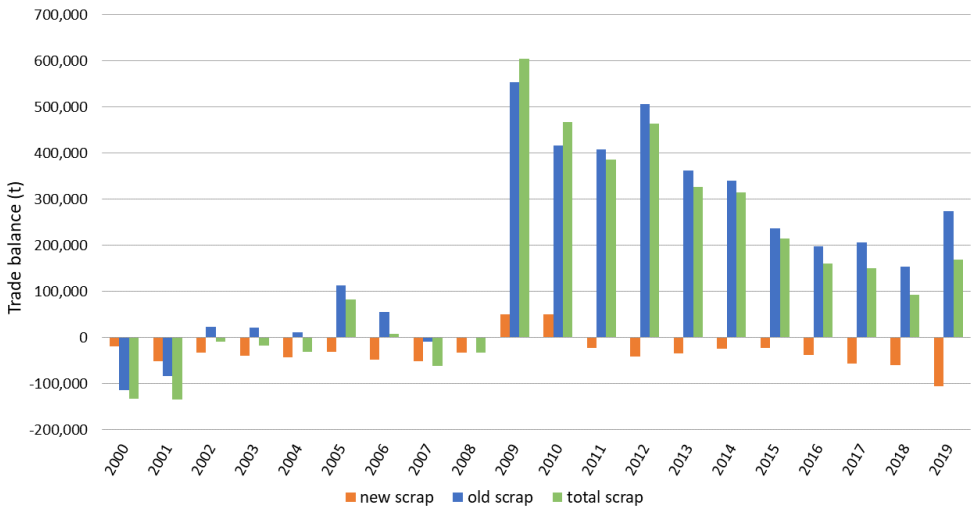
About 550 kt of valuable post-consumer scrap was exported outside the EU in 2019. The challenge of scrap outflows is discussed further in Section 6.4. Furthermore, the European Aluminium Association estimates to 600,000 tonnes per year the volume of aluminium scrap corresponding to the unknown whereabouts of EOL vehicles that are deregistered without a Certificate of Destruction (European Aluminium, 2020a).

6.4 Trade of secondary raw materials

Despite the great economic and environmental benefits of aluminium scrap recycling, the EU has become a net exporter since 2002 for valuable post-consumer (old) aluminium scrap. Before this, Europe was a modest importer of around 100 kt per year. Old scrap exports recorded a dramatic increase in 2009, and total net exports of scrap rose to the tune of 600 kt. Since 2012, scrap exports have been slowly declining, but the overall trend of positive net exports is not reversed; on the contrary, exports and net exports rebounded in 2019 (Figure 62). EU exports are mostly destined to Asian countries (Figure 63).

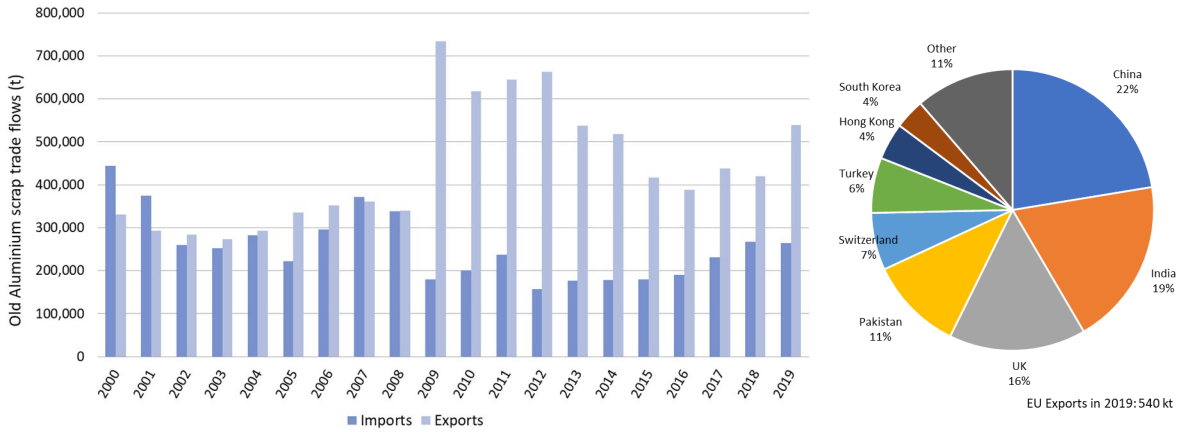
([127]) 40% according to (Saveyn et al., 2014)

Figure 62. EU trade balance of recyclable aluminium scrap ([128]) ([129])



Source: Background data in (Eurostat, 2020b).

Figure 63. Evolution of trade flows (left), and EU export destinations in 2019 (right) for old aluminium scrap (CN 76020090)



Source: Background data in (Eurostat, 2020b).

In Europe, scrap availability of unsorted scrap, i.e. scrap that is too mixed or highly alloyed to be used for wrought alloys, is higher than the demand for recycled castings leading to net exports to other regions. It is reported that if Europe was to recycle all its scrap domestically, then alloy to alloy separation for wrought alloys (rolling and extrusion scrap) would need to increase from 65% to 75% (Bertram *et al.*, 2017).

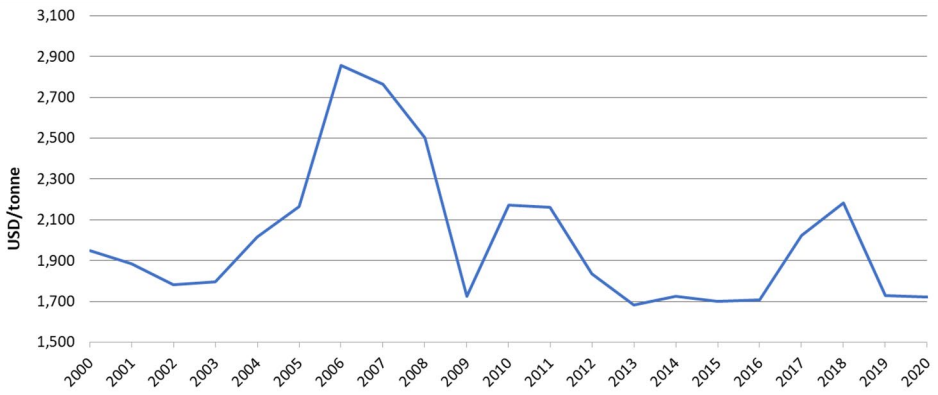
Many countries applied several export barriers (export ban, export tax or export licensing) in the period 2009-2019 for aluminium scrap worldwide; hence, available sources of aluminium scrap in global markets are fewer. Concerning major scrap generating countries, China has imposed an export tax of 15% since 2009, and the Russian Federation has introduced an export tax of 50% in 2007 that has decreased gradually to 10% in 2017 (OECD, 2020).

([128]) According to the Combined Nomenclature Explanatory Notes (European Commission, 2019a), new scrap is considered to consist of CN subheadings 7602.00.11 '*Turnings, shavings, chips, milling waste, sawdust and filings, of aluminium; waste of coloured, coated or bonded sheets and foil, of a thickness "excl. any backing" of <= 0,2 mm, of aluminium*' and 7602.00.19 '*Waste of aluminium, incl. faulty workpieces and workpieces which have become unusable in the course of production or processing (excl. slag, scale and other waste from the production of iron or steel, containing recyclable aluminium in the form of silicates, ingots and other primary forms, of smelted waste or scrap, of aluminium, ash or the residues of the production of aluminium, and waste in heading 7602.00.11)*'. Old scrap is represented by CN subheading 7602.00.90 '*Scrap of aluminium (excl. slags, scale and the like from iron and steel production, containing recoverable aluminium in the form of silicates, ingots or other similar unwrought shapes, of remelted waste and scrap, of aluminium, and ashes and residues from aluminium production)*'.

([129]) Positive bars represent 'net exports' and negative bars 'net imports'.

More important, the enormous rise in exports of aluminium scrap from the EU in 2009 coincided with the global financial crisis, and the subsequent collapse of aluminium demand and worldwide prices. The aluminium LME price fell significantly by about 35% in real terms from 2008 to 2009 (see Figure 64). Yet, despite the world financial crisis in 2009, the explosive growth of aluminium demand in China and other Asian countries remained unharmed, growing by 12% and 6% respectively in 2009. In contrast, in the rest of the world regions, aluminium demand plummeted by 22% ([130]). China and India needed to import more scrap for domestic use due to increased consumption in their building and construction industries and demand from their fast-growing transport sectors (Saveyn *et al.*, 2014).

Figure 64. Annual London Metal Exchange (LME) aluminium settlement ([131]) price, unalloyed primary ingots of a minimum 99.7% purity, in USD/tonne, real prices ([132])



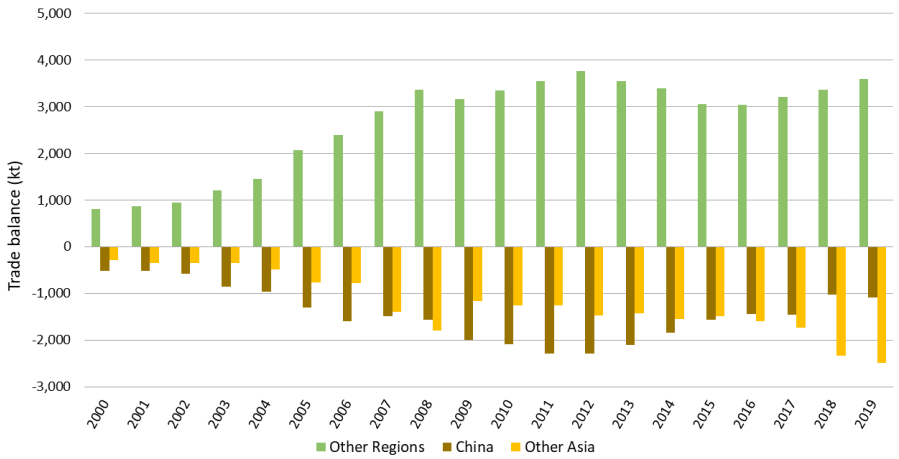
Source: Background data from (World Bank, 2021).

Figure 65 demonstrates the evolution of aluminium scrap's trade flows in China and other Asian countries, i.e. the principal destinations of EU exports of aluminium scrap, and Figure 68 the trend in recycled aluminium ingot production in these regions. Chinese net imports rallied from 2000 to 2012; since then, a steady slide is observed to lower levels. However, the production of recycled aluminium ingots in China held steady its steep rising trend up to 2017. Simultaneously, net imports from other Asian countries rocketed from 2000 to 2007 and, afterwards, fluctuated to high levels till 2017. In 2018 and 2019, the production of recycled aluminium ingots and net imports in other Asian countries hit record annual highs.

The above trends in the destination markets of EU aluminium scrap can be explained by the significant increase in domestic scrap availability in China, whereas in other Asian countries, the increase in the collected volumes of aluminium scrap to cover domestic demand was not as high (see Table 9). At the same time, the gigantic primary aluminium production in China (see Figure 8) covered most of the rapid increase in China's aluminium demand. Contrarywise, other Asian countries hold a minor share of global primary aluminium production; therefore, their secondary aluminium raw materials' needs continued growing.

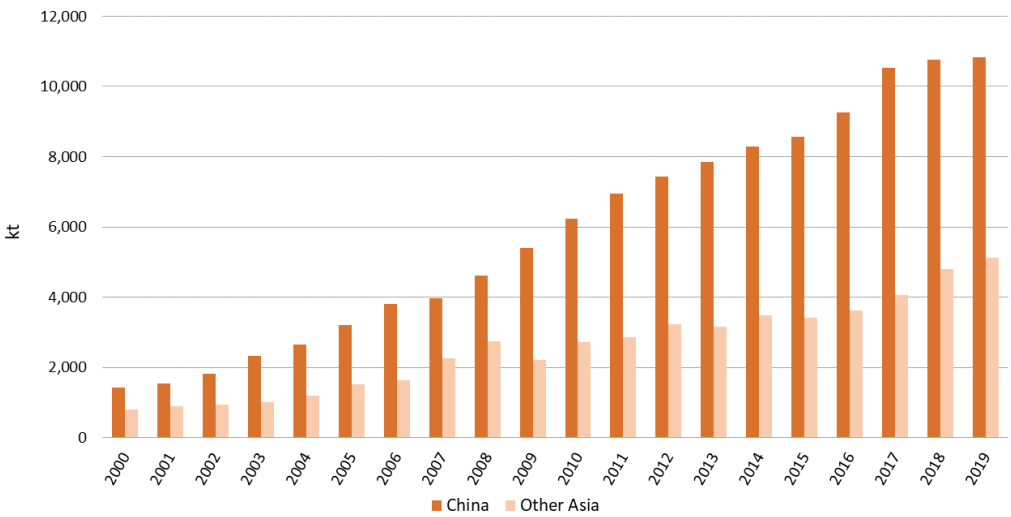
([130]) Data from Alucycle (IAI, 2020d) corresponding to 'manufacturing'
([131]) Settlement price beginning 2005; previously cash price.
([132]) Real prices in 2010 US dollars, adjusted for inflation.

Figure 65. Global trade balance of recyclable aluminium scrap by selected regions ([133]) ([134])



Source: Background data from (IAI, 2020d).

Figure 66. Production of recycled aluminium ingots in China and other Asian countries



Source: Background data from (IAI, 2020d).

Table 10. Scrap collection rates by selected world regions, in kg per capita

Region	Old Scrap			New Scrap			Total aluminium Scrap		
	2000	**2010**	**2019**	**2000**	**2010**	**2019**	**2000**	**2010**	**2019**
China	0.35	1.01	3.14	0.45	2.13	3.84	0.80	3.15	6.98
Other Asia ([1])	0.16	0.32	0.56	0.19	0.50	0.76	0.35	0.82	1.32
Europe ([2])	2.32	4.30	6.19	1.76	2.74	2.72	4.08	6.54	8.91
Rest-of-the-world	2.03	2.65	3.04	1.04	0.96	1.17	3.06	3.61	4.21

([1]) India, Indonesia, Malaysia, Pakistan, Singapore, South Korea, Taiwan, Thailand, Vietnam (Bertram et al., 2017).
([2]) As described in (Bertram et al., 2017), Europe comprises EU27 countries, Iceland, Moldova, Montenegro, North Macedonia, Norway, Serbia, Switzerland, Turkey, Ukraine.

Source: Background data from (IAI, 2020d).

([133]) 'Other Asia' includes India, Indonesia, Malaysia, Pakistan, Singapore, South Korea, Taiwan, Thailand, Vietnam (Bertram et al., 2017).
([134]) Positive bars represent 'net exports' and negative bars 'net imports'. Net exports of 'Other regions' are equal to net imports of 'China'+'Other Asia'.

The leakage of a highly recyclable raw material outside the EU is a barrier to the full exploitation of aluminium's circularity potential in the EU. An increase of secondary producers' output using the scrap collected domestically would facilitate lower environmental impacts, including a lower carbon footprint for the aluminium produced and used in the EU, as discussed in Sections 3.1.1 and 4.6.1. Besides, given that in the medium- and longer-term demand for aluminium will continue to increase, secondary production is a means to prevent the EU from becoming more dependent on imports; thus, it is a pivotal contributor to supply security.

6.5 Utilisation of solid wastes

6.5.1 Bauxite residues from alumina refining

The bauxite residue (BR), known as red mud, is produced in the form of a red slurry during alumina refining from bauxite. It contains the residues from the digestion of bauxite ores with caustic soda in the Bayer process, i.e. not dissolved iron minerals and other non-alumina bearing bauxite minerals, as well as liquor desilication products (calcium and sodium aluminosilicate precipitates). Elements found in the bauxite residue include iron, silicon, titanium, and others in small quantities, including scandium and gallium (Zinoveev *et al.*, 2021)(Wang *et al.*, 2019) (Balomenos, 2019) (Lu *et al.*, 2018).

The management of bauxite residue (BR) (also known as 'red mud') represents a major challenge for sustainable disposal or recovery due to its enormous volume, the high alkalinity (pH about 10.5–13.5 (Reddy *et al.*, 2021)), contents of trace radioactive elements and other potentially harmful elements. The possible environmental impacts caused by the BR comprise emissions to surface water and groundwater and emissions to air because the wind can easily disperse fine-grained particles. In addition, a large storage area is needed, which may require the management of dams. Leaks caused by damage to pipelines, failure of retaining dams, and the leaching of alkaline solution from the containing barrier can have substantial environmental impacts (Wang *et al.*, 2019).

The specific amount and composition of bauxite residues depend on the bauxite ore quality and alumina extraction conditions. For each tone of alumina produced, between 600 kg and 1,500 kg of BR are generated (Cusano *et al.*, 2017). In the EU+UK+EFTA countries, the BR volumes generated in alumina production in 2015 amounted to about 800 kg/t alumina, of which only 1.5% was valorised as a by-product (see Figure 43). Bauxite residue (BR) generation is estimated in excess of 150 million tonnes worldwide each year (Balomenos, 2019). The combined stock of bauxite residue is estimated to over 4.6 billion tonnes globally by (Zinoveev *et al.*, 2021) and between 3 and 4 billion tonnes by (Balomenos, 2019). Current scenarios based on the International Aluminium Institute's material flow model indicate a doubling of the global inventory of BR by 2040, i.e. to 7 to 8 billion tonnes (IAI, 2020e).

In the EU, alumina refineries operate in France, Germany, Greece, Ireland, Romania, and Spain (Table 11). Significant BR stocks from refineries that have stopped their operations exist in Italy, France, Germany, Hungary and other countries. The current BR production in the EU is about 6 Mt/y, and the cumulative stockpiled level is estimated to exceed 250 Mt (dry matter) (Balomenos, 2019). The ever-growing demand for BR disposal space ultimately threatens the longevity of established alumina refineries, particularly when land availability is becoming limited. BR disposal in the alumina refinery in Greece takes up 1 km^2 of land for an annual 0.75 Mt BR deposit. At the Auginish plant in Ireland, the management of the 1.2 Mt of BR produced annually results in the current land use of 1.83 km^2 (Balomenos, 2019).

Table 11. EU alumina refineries and BR generation

Plant	Country	Company	Estimated Red Mud generation annually (kt, dry basis)
Aughinish	Ireland	Aughinish Alumina Ltd	1,800
San Ciprián	Spain	Alcoa World Alumina and Chemicals (AWAC)	1,350
Stade	Germany	Aluminium Oxid Stade (AOS) GmbH	950
Agios Nikolaos	Greece	Aluminium of Greece	750
Gardanne	France	Alteo	570
Tulcea	Romania	Alum	540
Total			5,960

Source: (Balomenos, 2019) for red mud estimates; (BGS, 2020) for alumina production; S&P Global database and company websites for operators.

The common practice is to deposit BR in the form of slurry (30-50% wt. solids, 4-6% wt. Na_2O) in specially designed, sealed settling ponds. Excess water from the ponds is generally returned to the process (Cusano *et al.*, 2017). The alkalinity of associated liquid phase can be substantially reduced by improved washing and effective dewatering techniques (Reddy *et al.*, 2021). Hence, many refineries are moving towards high-pressure filtration as a last treatment step for red mud dewatering in order to enable dry disposal. The bauxite residue is pressed to remove as much as possible the remaining liquor and produce a compact filter cake (Balomenos, 2019). The output from this operation is a moist material with a relatively low moisture content (solid content of about 75% wt., and a remaining soda content of 1-3% Na_2O), which can be easily trucked or put on a conveyor belt either for disposal either for use (Balomenos, 2019). A lower moisture level (<20%) can be achieved after solar drying (IAI, 2020f). Compared with the residue's storage in slurry form in lagoons, dry stacking enables storage in higher piles using less land, eliminates the risk of flooding adjacent areas, and enables better recovering of the caustic liquor entrained in the residue (Hydro, 2012).

As BR constitutes a severe environmental issue for the aluminium industry, and its generation will continue at massive volumes for many decades, the industry and scientific research are exploring intensively technologies for red mud processing to reduce the volume for disposal through its cost-effective utilisation. Annex 5 provides an overview of EU-funded research projects since 2010 for the utilisation of bauxite residues. No cost-effective integrated technologies exist so far for the complete recycling of BR on a large industrial scale (Zinoveev *et al.*, 2021). Strength and alkalinity are identified as the major restrictive factors to boost the use of BR (Reddy *et al.*, 2021).

The most widespread use of bauxite residues globally is in Portland cement clinker production as a supplementary iron or alumina source, in substitution of primary raw materials. The benefits are reduced waste generation for alumina producers, in addition to improved energy efficiency and lower CO_2 emissions in clinker production (IAI, 2020e). The critical aspects for the successful industrial accommodation of bauxite residue in the clinker production are the moisture level and the Na_2O content, limitations imposed by processing chemistry, the aluminium oxide to iron oxide ratio, the relative costs of primary iron and alumina sources in the area, and the proximity of cement plant to keep transport costs low (IAI, 2020f). It is estimated that over 3 Mt of bauxite residue is currently used in the cement industry around the world as a raw material in clinker production (IAI, 2020e), i.e. approximately 2% of the annual BR production is currently valorised to saleable products. In the EU, cement plants now using bauxite residue are located in Greece, Romania and Cyprus (IAI, 2020e). In 2019, the Agios Nikolaos refinery in Greece supplied about 80 kt of BR to cement plants, and the potential to increase BR's utilisation is by 300 kt per year (IAI, 2020f).

Numerous treatment technologies and solutions have been researched to enable its productive use in several other applications. Apart from Portland cement clinker, the filtered/dried bauxite residue could be utilised in supplementary cementitious materials for blended and special cements (IAI, 2020e). Other potential technological solutions include the tile & bricks industry substituting clay, geopolymers, road base construction, substitute of iron ore as the average iron content is about 40%, landfill barrier/cover or backfilling of closed bauxite mines etc.; however, without robust financial viability (Balomenos et al., 2017).

Last but not least, European bauxite residues contain small concentrations of critical raw materials. In particular, the Greek bauxite residues (mainly originating from Greek bauxites) have a relatively constant amount of REEs

of about 1 kg per tonne (Balomenos, 2019). The FP7 EURare R&I project investigated the potential of extraction of rare earth elements (REE) from bauxite residue originating from REE-enriched bauxites (EURARE, 2017). The BR are also a promising resource for Scandium as it can contain up to 120 g/t Sc (Zinoveev *et al.*, 2021), a critical raw material with advanced technological applications. Greek bauxite residues seem to significantly favour a commercially viable recovery of Sc under an optimal combination of leaching and separation techniques (Ochsenkuehn-Petropoulou *et al.*, 2018). The Horizon 2020 SCALE project is researching the recovery of Scandium (Sc) from bauxite residues, aiming at the scale up of industrial development of a Sc-selective leaching process of Bauxite Residue (SCALE, 2020). Finally, the BR is a potential resource for gallium, which is found in bauxite ores at average levels of about 50 ppm (Foley *et al.*, 2017) and is dissipated in the alumina and BR streams (Balomenos, 2019). The BR generally contains 20–80 ppm of gallium (Lu *et al.*, 2018). Extracting gallium from both the BR and Bayer liquor from a single European alumina refinery could reach global levels of gallium production, i.e. about 280 tonnes annually (Balomenos, 2019).

6.5.2 Salt Slag from secondary aluminium production

The disposal of aluminium salt slag, which is a residue generated during old aluminium scrap and/or dross melting under a salt layer, is a worldwide problem (Tsakiridis, 2012). Salt flux is used mainly in rotary furnace in order to collect the contaminants within the salt slag (also known as salt cake) and prevent molten metal from oxidation. The quantity of salt slag generated in secondary aluminium production processes varies and is dependent on the type of material, the furnace and the degree of contamination of aluminium scrap (Cusano *et al.*, 2017). Salt slag is classified as hazardous waste (highly flammable, irritant, harmful and leachable). It has adverse environmental impacts in the event of improper land disposal, such as leaching of toxic metal ions into groundwater (Tsakiridis, 2012).

Most of the salt slag is treated to recover the aluminium metal it contains (between 4 and 10%) and regenerate the salt flux (a mixture of NaCl, KCl and a minor amount of calcium fluoride ranging from 20% and 55%) (Cusano *et al.*, 2017). The non-metallic residue (mainly oxides of aluminium, calcium and magnesium) could be landfilled or utilised in a variety of applications after further processing, such as the production of cements, in ceramic and refractory applications, in chemical and metallurgical industry, enhancing the profitability of the total recycling process (Tsakiridis, 2012). There is sufficient capacity to recover salt slag from the secondary aluminium industry operating in the EU (Cusano *et al.*, 2017).

7 Economic aspects

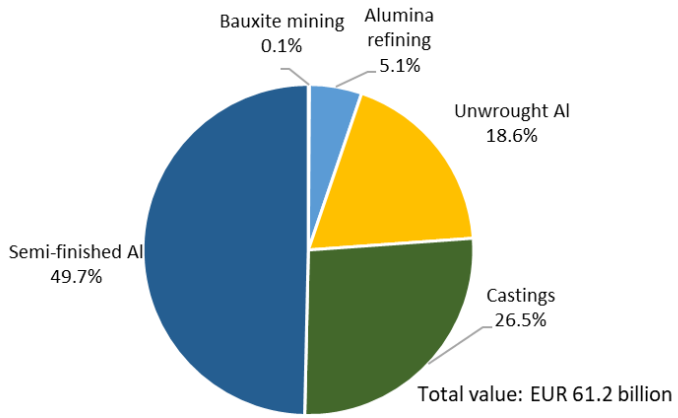
7.1 Economic importance in the EU

The annual turnover of the aluminium sector ([135]) in the EU amounted to more than EUR 61 billion in 2018 that represents about 0.9% of the total production value of the EU manufacturing sector (Eurostat, 2020a). The sector also directly represents a workforce of about 225,000 people throughout the entire value chain, i.e. from alumina production and metal supply to semi-finished products and castings. The contribution of the total value added to the EU economy was EUR 14.6 billion in 2018, split in EUR 9.2 billion for the economic activity NACE 24.42 'Aluminium production', and EUR 5.4 billion for the NACE 24.53 'Casting of light metals' (Eurostat, 2020a)(Eurostat Prodcom, 2020). The Industrial Strategy for Europe ([136]) places a new focus on industrial ecosystems to encompass all players operating along a value chain. Aluminium is relevant to 10 of 14 industrial ecosystems([137]); hence, it has significant interlinkages with other industries in the Single Market.

The EU aluminium industry is composed of small and medium-sized enterprises, besides integrated large companies. The economic activity classified under NACE 24.42 'Aluminium production' encompassed 1,273 enterprises in 2018, from alumina refining to semi-finished manufacturing. The closely related industrial sector of light metals casting belonging to NACE 24.53 comprised 1,600 enterprises (Eurostat, 2020a), where aluminium castings are the predominant product (CAEF, 2019).

According to Eurostat data, half of the overall turnover was achieved by the downstream producers of semi-finished aluminium products (rolled, extruded and wire), and more than one quarter from companies engaged in the production of castings (Figure 67). The production value for the upstream segments in the aluminium value chain in the EU is much lower, i.e. about 5% for alumina and minimal at 0.1% for bauxite.

Figure 67. Production value per segment of the EU value chain([138]), in 2018



Source: Background data from (Eurostat Prodcom, 2020).

([135]) It is considered that the aluminium sector is represented by NACE 24.42 '*Aluminium production*' and NACE 24.53 '*Casting of light metals*' in Eurostat statistics. NACE 24.42 'Aluminium production' includes: production of aluminium from alumina, production of aluminium from waste and scrap, production of aluminium alloys, semi-manufacturing of aluminium, manufacture of wire of these metals by drawing, production of aluminium oxide (alumina), production of aluminium wrapping foil, manufacture of aluminium foil laminates made from aluminium foil as primary component. Mining is not included under NACE 24.42. NACE 24.53 '*Casting of light metals*' includes casting of semi-finished products of aluminium, magnesium, titanium, zinc etc., and casting of light metal castings. About 99% of light metal castings output is made of aluminium (CAEF, 2019).

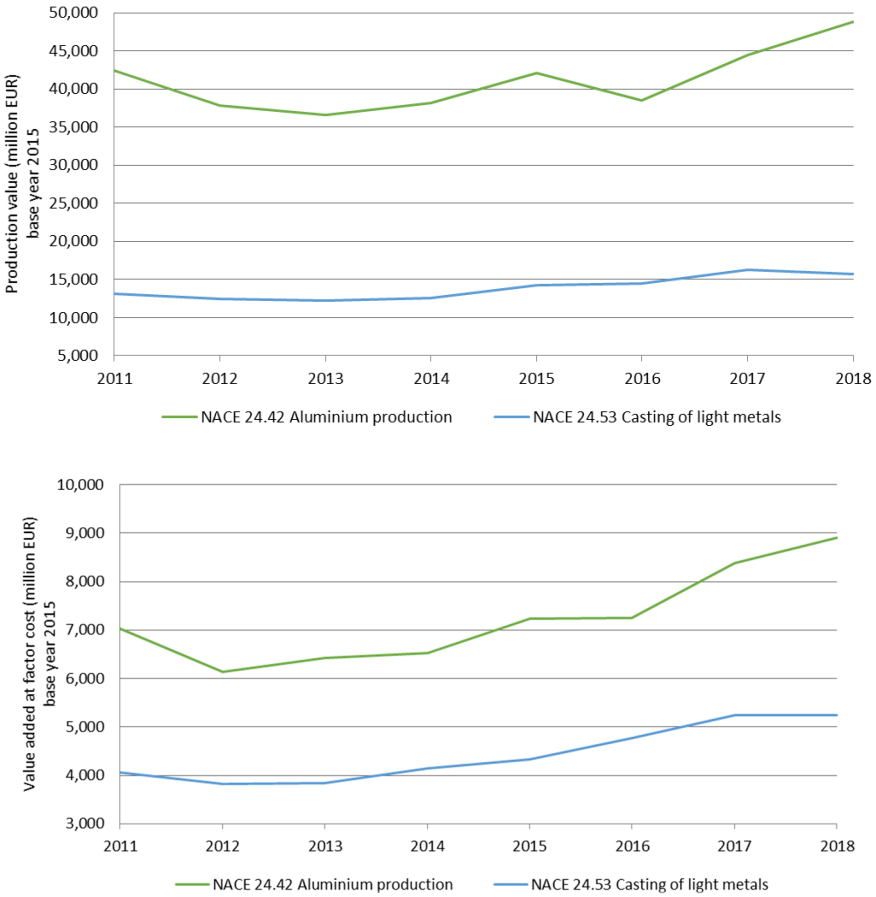
([136]) COM(2020) 102 final

([137]) As bauxite in COM(2020) 474 final. 14 industrial ecosystems were preliminary identified in the Staff Working Document (SWD(2020) 98) accompanying the Recovery Plan (COM(2020) 456). Relevant ecosystems are: Aerospace/defence, Textiles, Electronics, Mobility/Automotive, Energy-intensive industries, Renewable energy, Agri-food, Health, Digital, Construction

([138]) Mine products comprise Prodcom codes for bauxite (07291300). Alumina products refer to Prodcom codes for metallurgical and speciality alumina (24421200, 23991500, and 20132570). Semifinished aluminium products include Prodcom codes for plates, sheets, strips, and foil (24422430, 24422450, and 24422500), bars, rods, profiles, tubes, pipes and fittings for tubes and pipes (24422230, 24422250, 24422630, 24422650, and 24422670), and wire (24422330, and 24422350). Unwrought aluminium products include Prodcom codes for unwrought aluminium ingots (24421130, and 24421154) and powders & flakes (24422100). The production value for castings corresponds to the figure of production value reported for NACE Rev.2 sector 24.53 "*Casting of light metals*".

The following figure demonstrates the trend in production value and value added at factor cost for the EU aluminium industry (normalised values). It is noted that from 2011 to 2018, the production value for NACE 24.42 and NACE 24.53 rose by 15% and 19% respectively, and by 16% in total for both sectors. In the same period, the total value added at factor cost increased with a noteworthy higher rate of 28% (27% for NACE 24.42, and 29% NACE 24.53). This trend implies that the European aluminium industry managed to achieve lower costs of production in the period 2011-2018 or/and shifted to products of higher value added for its customers in various industries. For NACE 24.42 in particular, an increase of about 10% is observed for the value added at factor cost from 2014 to 2016 despite the steady production value, while production value and value added rose strongly in 2017-2018. For NACE 24.53, the rising trend in both indicators is stable from 2013 to 2017, whereas in 2018 the increase was flattened out.

Figure 68. Production value (top) and value added at factor cost (bottom) (NACE 24.42 and NACE 24.53) ([139])



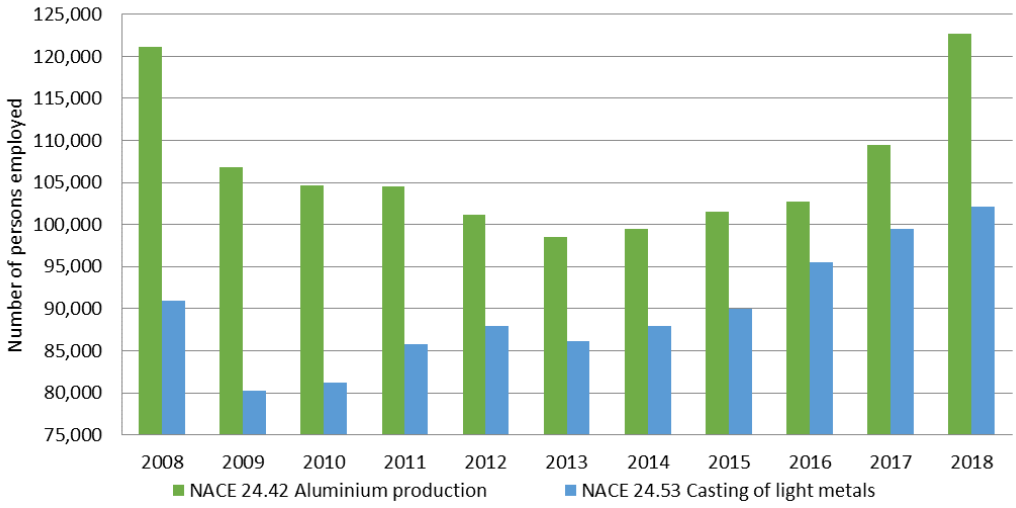
Source: Background data from (Eurostat, 2020a).

7.2 Employment in the EU

In 2018, the aluminium industry (NACE 24.42) provided direct employment for 123,000 people in the EU and the UK. The number of employees in 2018 has risen by almost 25% since the most recent lowest point in 2013 and overpassed the level achieved before the financial crisis of 2009. Concerning the sector of light-metal castings (NACE 24.53), approximately 102,000 persons were directly employed in 2018. Compared to 2013, this represents a rise of 19% (see Figure 69). The European Aluminium Association estimates that together with indirect jobs, one million jobs are dependent on aluminium across the whole value chain ([140]) (European Aluminium, 2018a). Germany, Italy, France and Poland are the EU Member States with the largest direct employment levels for NACE 24.42 and NACE 24.53 (see Figure 70).

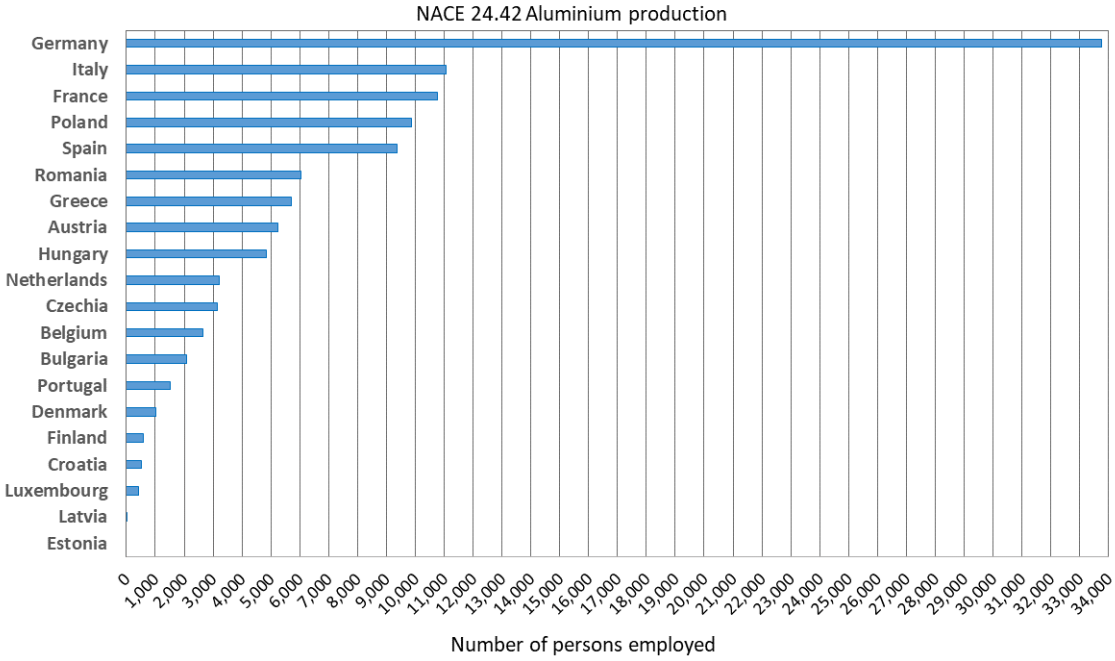
([139]) Values are normalised for inflation using the annual average Harmonised Index of Consumer Prices (HICP), Base year 2015.
([140]) The International Aluminium Institute has identified a multiplier effect of 3.7 to calculate indirect employment in the global aluminium industry (IAI, 2021c).

Figure 69. Direct jobs in the aluminium and light metal castings industry EU and UK([141]) (NACE 24.42 and NACE 24.53)



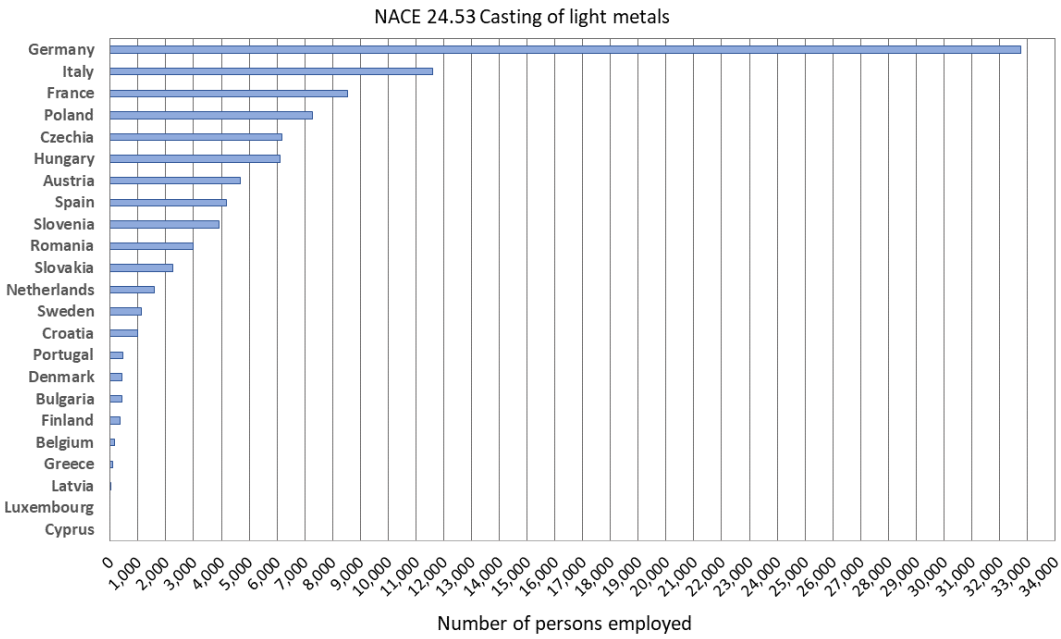
Source: Background data in (Eurostat, 2020a).

Figure 70. Direct jobs in the EU aluminium industry by countries ([142]) in 2018, NACE 24.42 (top) and NACE 24.53 (bottom)



([141]) Data are not available for EU27 for all years

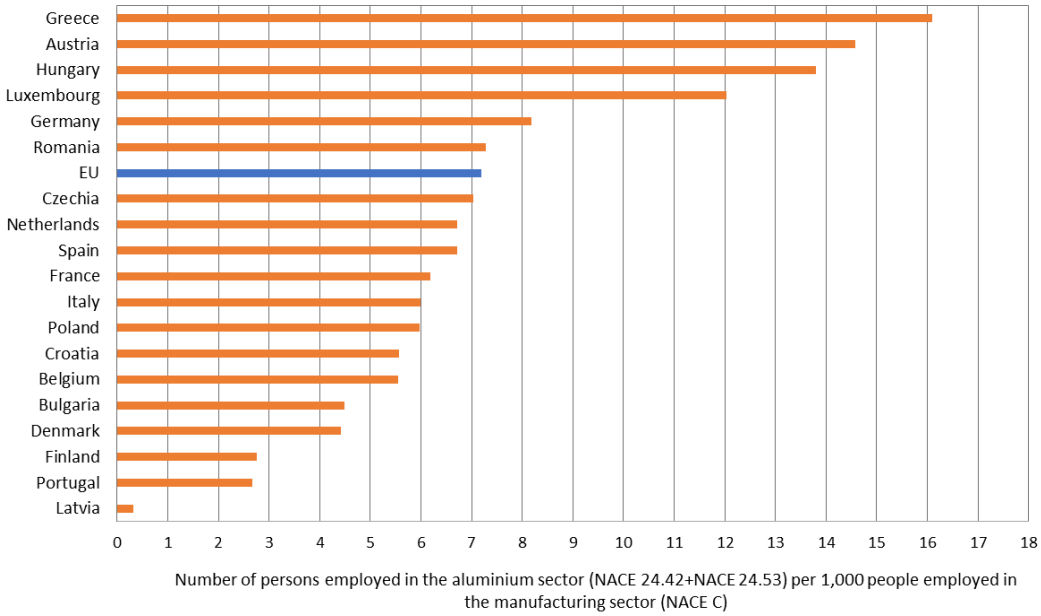
([142]) For NACE 24.42 data are confidential for Ireland, Cyprus, Lithuania, Malta, Slovenia, Slovakia and Sweden. For NACE 24.53 data are withheld for Estonia, Ireland, Lithuania and Malta.



Source: Background data in (Eurostat, 2020a).

Figure 71 shows the share of jobs in the aluminium industry sectors (NACE 24.42 + NACE 24.53), compared to the total employment in manufacturing. The aluminium industry has the highest share of employment in the manufacturing base of Greece, Austria, Hungary, and Luxemburg, therefore highly relevant for their national economies. Concerning the Member States having the top levels of direct jobs in the aluminium industry, as shown in Figure 70, only Germany's percentage of the total employment in manufacturing is above the EU average.

Figure 71. Employment in the EU aluminium industry by countries over the total employment in industry, in 2018 ([143])



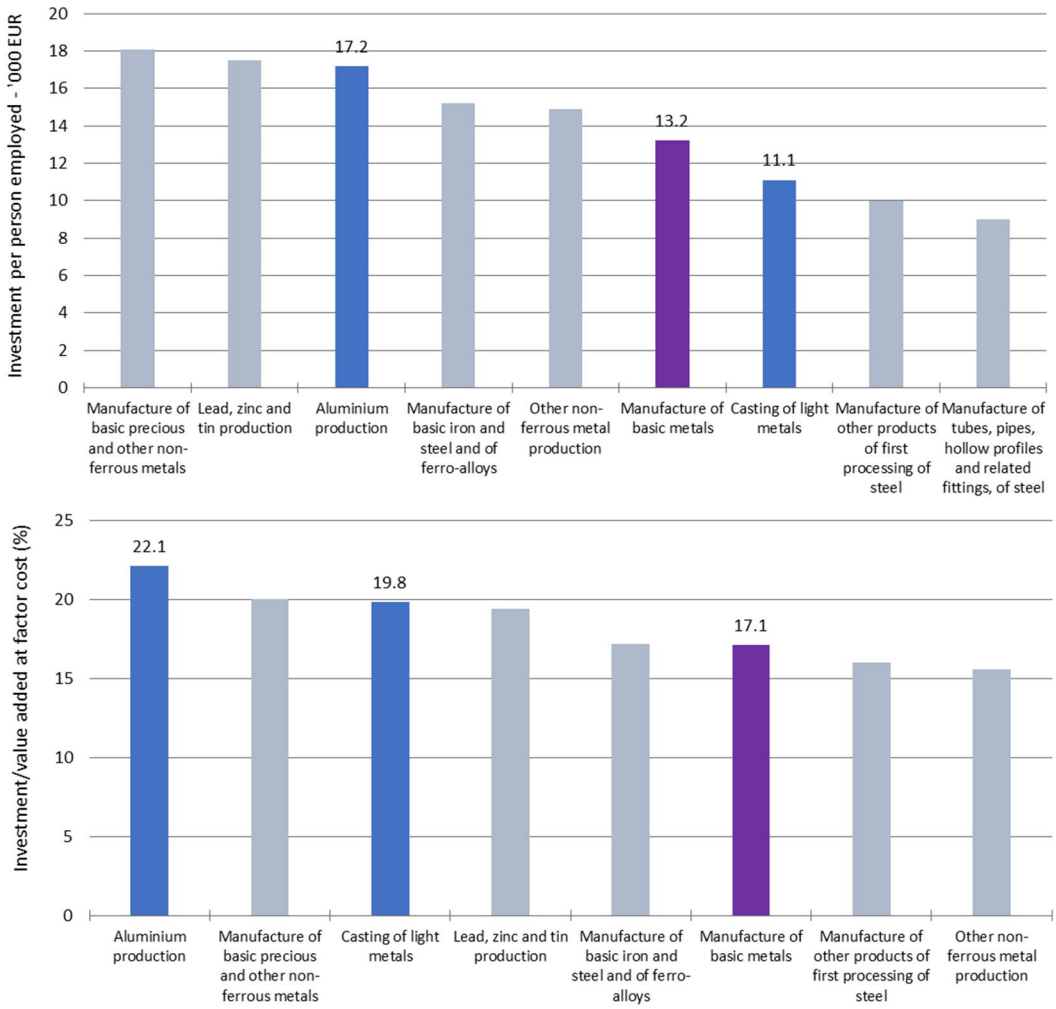
Source: Background data in (Eurostat, 2020a).

([143]) Data for Ireland, Cyprus, Estonia, Ireland, Lithuania, Malta, Slovakia, Slovenia, and Sweden are not disclosed in the source.

7.3 Investments

The investment intensity in the EU aluminium industry (NACE 24.42 'Aluminium production') is greater than the average of the metals sector (NACE 24 'Manufacture of base metals'). The Figure below shows the investment intensity for several industrial metal-producing sectors in 2018. Aluminium production (NACE 24.42) recorded the highest level of investments per generated value added among all the EU metal sectors, which is notable considering the record value added at factor cost in 2018 (see Figure 68). The investment figures suggest that the Union's aluminium industry kept investments high in 2018 in order to remain competitive, for instance to increase efficiency and move towards higher value-added products ([144]).

Figure 72. Investment per person employed (top) and investment as a proportion of value added (bottom) in sectors of industrial metals in the EU, by descending order, in 2018



Source: Background data from (Eurostat, 2020a).

([144]) The analysis of more indicators per segment of the aluminium industry, such as the return on investment and profitability, is required for the assessment of investment performance.

8 Concluding remarks

Aluminium and its value chain are assessed to be one of the key materials in the worldwide efforts to combat global warming and for Europe's transition to a climate-neutral and circular economy. The biggest environmental challenge facing aluminium industry today is the GHG emissions associated with primary aluminium production. Emissions can be significantly reduced by using low-carbon electricity. Future production will likely move towards less energy-intensive pathways reflecting the pace of decarbonisation to achieve the 2050 vision. Moreover, the positive environmental contribution of aluminium used in various applications such as transport, construction and energy technologies may more than offset the initial impacts of production.

Carbon emissions isn't the only pressing sustainability issue facing aluminium. Deforestation in areas of rich biodiversity where bauxite is mainly mined, and the bauxite residues' management are also of prime concern. As increasing aluminium's recycling rates is a concrete step to save energy and carbon emissions, as well as to enhance Europe's strategic autonomy for raw material inputs for an extensive domestic industrial base creating billions of value-added and employment, industry players and other parties involved in the aluminium value chain must aspire for higher recycling rates to unlock aluminium recycling's full potential.

Concerns on the social sustainability of aluminium value chain emerged in the upstream stage of the value chain, and in particular on the governance of the bauxite sector in Guinea and other producing countries. Environmental conflicts worldwide for bauxite exploration and new mine development also imply a lower integration with local communities compared to downstream stages. Instead, the aluminium industry in the EU has demonstrated relevant improvements in their social performance. This confirms the importance of ensuring responsible sourcing of materials in the process of EU decarbonisation, e.g. sufficient attention is needed to deforestation in tropical forests in EU bauxite sourcing countries, in order to avoid impacts externalization to third countries and ensure a fair transition to a low-carbon economy.

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List of abbreviations

AC	Alternating current
ADP	Abiotic Depletion Potential
AHSS	Advanced high-strength steel
ASI	Aluminium Stewardship Initiative
ASI	Aluminium Stewardship Initiative
BAT	Best Available Technique
B2DS	Beyond 2 Degree Scenario
BR	Bauxite residue
BREF	Best Available Techniques reference document
CAGR	Compound annual growth rate
CBG	La Compagnie des Bauxites de Guinée
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon capture, utilisation & storage
CLP	Classification, Labelling and Packaging
CO2eq	Carbon Dioxide equivalent
DC	Direct current
EC	European Commission
EDC	Ecological distribution conflict
EF	Environmental Footprint
EFTA	European Free Trade Association
EITI	Extractive Industry Transparency Initiative
EJ Atlas	Environmental Justice Atlas
EoL	End-of-Life
EoL-CMU	End-of-Life Circular Material Use
EOL-CR	End-of-Life Collection Rate
EOL-RIR	End-of-Life Recycling Input Rate
EOL-RR	End-of-Life Recycling Rate
EPI	Environmental Performance Index
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse gases
GWP	Global Warming Potential
HRW	Human Rights Watch
IAI	International Aluminium Institute
ICE	Internal combustion engine
ICMM	International Council on Mining & Metals
IED	Industrial Emissions Directive
LCA	Life Cycle Assessment

MDS	Medium-demand scenario
MFA	Material Flow analysis
MSA	Material System analysis
NACE	Statistical classification of economic activities in the European Community (Nomenclature Statistique des Activités Économiques dans la Communauté Européenne)
NCA	Nickel-Cobalt-Aluminium
OHS	Occupational Health and Safety
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PFC	Perfluorinated compounds
PV	Photovoltaic
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RGI	Resource Governance Index
SAP	Special Area of Protection
SCI	Site of Community Importance
SDG	Sustainable Development Goal
SMB	La Société Minière de Boké
TRI	Total Recordable Incident
UK	United Kingdom
USGS	United States Geological Survey
WPC	Wood Products with Chemicals
WWF	World Wildlife Fund

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Annexes

Annex 1. Basic assumptions, sources and definitions

Asset-level data from the S&P Global Market Intelligence database were used in the analysis involving resources, capacity and/or production of facilities worldwide. The information provided by S&P Global Market Intelligence per site includes activity and development status, operators and ownership, resources, capacity and annual production per commodity, and geospatial reference. This information was combined with data from other sources (such as company websites and reports) to fill gaps and increase coverage. The datasets were organized by bauxite mines, alumina refineries and primary aluminium smelters. The built database was also used to correlate installations (mines, refineries, and smelters) with ASI certified mines and plants, as well as to associate exploration projects, mines and plants with environmental conflicts.

As currently operational sites were considered those mine with activity status classified as 'active' and 'temporarily on hold', and their development status as ´operating´, ´expansion´. ´satellite´, or 'limited production' by the S&P Global Market Intelligence database.

Since the S&P Global Market Intelligence database does not provide a full coverage of all operating assets, and/or necessary background information such capacity/production/geolocation/status, the following methodological approach was employed to increase the coverage and fill data gaps:

- When the bauxite mine capacity was not reported on a mine site/asset basis by S&P Global or other sources, it was estimated using the production of year 2018 and the average capacity utilisation rate (81%), as derived from the utilisation rates of operating mines in 2018 (for which production and capacity was both available). In case the 2018 production per mine site/asset was not available S&P Global or other sources, then the capacity was approximated using the average mine production for the previous three years (2015-2017) and the average capacity utilisation rate worldwide in 2018. When nor production neither capacity by asset/property was provided by S&P Global in the above timeframe, open-source statistics such as the World Mining Data and the British Geological Survey were employed to allocate the production of 2018 at asset level, if feasible to allocate the national aggregate to a specific mine site. Various sources were used to increase the coverage for the geolocation of mines, when not reported in the S&P Global database. Ultimately, the coverage attained for the bauxite mines' dataset is estimated at 80% of the global mine capacity, and the coverage for georeferenced currently operational bauxite mines at 71% of the global mine capacity;
- Capacities for alumina refineries were obtained from various sources. When the capacity was not available, the 2018 production level was used multiplied by a reasonable average capacity utilisation rate (85%);
- Capacities for primary aluminium smelters were sourced from (Pawlek, 2020).

Annex 2. Assessment of the Environmental Hazard Potential (EHPs)

The methodology applied in the study commissioned by the German Environmental Agency (UBA) took into account three levels that have an impact on the Environmental Hazard Potential (Dehoust *et al.*, 2020):

- The first level extended in the area of geology. In particular, the potential for Acid Mine Drainage (AMD), the likelihood of paragenesis with heavy metals and radioactive contamination were investigated (indicators1-3). For instance, raw materials that tend to occur in sulphide ores pose a higher Environmental Hazard Potential than raw materials occurring in oxidic sedimentary ores;
- The second level covered technological aspects of mining by assessing the mining method and the use of auxiliary substances (indicators 4-5). e.g. raw materials that are more likely to be mined in open-pit operations disturb larger surface areas than raw materials mainly mined underground;
- Finally, Dehoust et al. (2020) assessed the EHPs that emanate from the natural environment (indicators 6-8). This relates to the mine sites' geographic location and investigates hazard potentials due to floods, landslides, earthquakes and storms. e.g., if a majority of mines for a certain raw material are located in areas with frequently occurring floods, the Environmental Hazard Potential for the raw material is more likely to be high, since floods can be a cause of tailings dam failures. Moreover, it is determined whether mines are located in areas with high water stress or low water-availability (deserts) and if mining sites are located in protected areas.

The current report presents only the outcomes of Indicators 1-5 as the environmental background conditions covered by Indicators 6-8 are given elsewhere in the report using JRC data and analysis. The following table demonstrates the scheme employed by UBA to evaluate raw material-related environmental hazard potential for Indicators 1-5.

Table A1. Environmental Hazard potential evaluation

Indicators	Low	Medium	High
1. Preconditions for acid mine drainage (AMD)	Geochemical preconditions for AMD do not exist	Geochemical preconditions for AMD partly exist	Geochemical preconditions for AMD exist
2. Paragenesis with heavy metals	The deposits usually have no elevated heavy metal concentrations	The deposits usually have elevated heavy metal concentrations	The deposits usually have strongly elevated heavy metal concentrations
3. Paragenesis with radioactive substances	The deposits usually have low uranium and/or thorium concentrations	The deposits usually have slightly elevated uranium and/or thorium concentrations	The deposits usually have elevated uranium and/or thorium concentrations
4. Mine type	Commonly extracted in underground mines	Commonly extracted from solid rock open pit mines	Commonly extracted from alluvial or unconsolidated sediments and/or dredging in rivers
5. Use of auxiliary substances	Standard extraction & processing methods without auxiliary chemicals	Standard extraction & processing methods using auxiliary chemicals.	Standard extraction & processing methods using toxic reagents and auxiliary chemicals

Source: (Dehoust et al., 2020)

Annex 3. Methodology applied for the analysis of environmental conflicts

The analysis was based on the Environmental Justice and Socio-Environmental Conflicts (or equally, Ecological Distribution Conflicts) reported by the EJ Atlas related to bauxite and aluminium. The registered cases were screened to identify those relevant with specific bauxite exploration and mine development projects, alumina refineries and primary aluminium smelters. The considered development phases encompassed planning, construction, operation, expansion or closure. Cases with directly related logistics to the above projects and installations in the aluminium value chain were also included in the sample e.g., hydroelectric dams' construction and operation to supply electricity principally to aluminium smelters, ports for bauxite transport. Cases related to waste management or cases not associated directly with one of the above stages in the aluminium value chain were not taken into account. The sample was enriched by desk research to find recent or not reported by the EJ Atlas environmental conflicts in the aluminium value chain.

A production capacity was allocated to each identified as above project, mine, refinery or smelter (see Annex 1). The average capacity worldwide of operational bauxite mines was considered as a proxy of capacity for bauxite exploration projects. Qualitative and quantitative background information for each case, such as the conflict intensity, installation's locations, features of projects behind the conflicts, evolution of the conflict etc., was sourced from EJ Atlas and/or by online sources. The end year of the conflict was considered the year that the conflict ended or became latent with respect to the initial reasoning/resistance behind the conflict. For instance, as the end year of the conflict was considered the year of construction and operation of a new mine or plant which generated opposition in the planning/permitting phase, or the year that a court or administration decision allowed or prohibited the operation of a mine/plant that had triggered a conflict.

The EJ Atlas database is updated continuously and new cases are being registered on a frequent basis. However, the coverage of the conflicts cannot be deemed representative, but illustrative; still, it represents the world's largest existing database so far.

Annex 4. Assessment of recycling indicators

Table A1 demonstrates the calculation formulas for deriving the recycling indicators from the flows provided by International Aluminium's Alucycle MFA tool (IAI, 2020d).

Table A1. Recycling indicators' formulas.

Indicator	Formula
EOL-CR	(Collected old scrap) / (End-of-Life management)
EOL-RR	(Recycled ingot production X old scrap ratio in total scrap availability)/(End-of-Life management + imports of scrap – exports of scrap)
EOL-RIR	(Recycled ingot production X old scrap ratio in total scrap availability)/(Total ingot production)
EOL-CMU	(Collected old scrap + imports of scrap – exports of scrap)/ (Aluminium Use)

The formulas shown in Table A2 were used for the calculation of recycling indicators based on data from Aluminium's MSA study (Passarini et al., 2018). Table A3 and Figure A1 describe the individual flows (BIO by Deloitte, 2015).

Table A2. Recycling indicators' formulas.

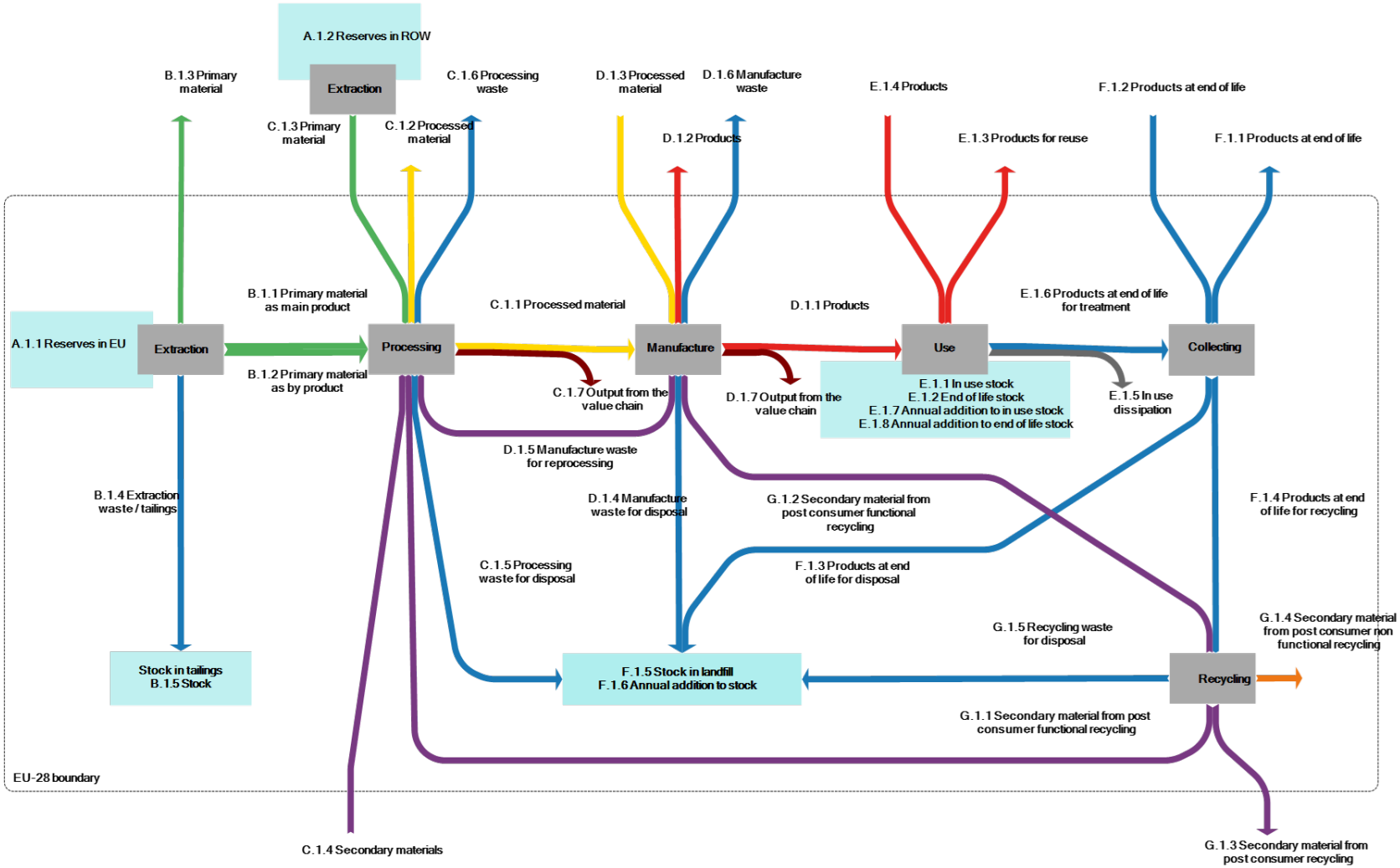
Indicator	Formula
EOL-CR	(F.1.4) / (E1.6)
EOL-RR	(G1.1+G1.2+G1.3) / (E1.6+F1.2-F1.1)
EOL-RIR	EOL-RIR=(G.1.1+G.1.2) / (B.1.1+B.1.2+C.1.3+D.1.3+C.1.4+G.1.1+G.1.2)
EOL-CMU	(G.1.1+G.1.2+G.1.3)+C.1.6+D.1.6+F.1.1-C.1.4-F.1.2)/(D.1.1+E.1.4)

Table A3. List of material flows and stocks parameters.

Material Flow/Stock Parameter
A.1.1 Reserves in EU A.1.2 Reserves in ROW
B.1.1 Production of primary material as main product in EU sent to processing in EU **B.1.2 Production of primary material as by-product in EU sent to processing in EU** B.1.3 Exports from EU of primary material B.1.4 Extraction waste disposed in situ/tailings in EU B.1.5 Stock in tailings in EU
C.1.1 Production of processed material in EU sent to manufacture in EU C.1.2 Exports from EU of processed material **C.1.3 Imports to EU of primary material** **C.1.4 Imports to EU of secondary material** C.1.5 Processing waste in EU sent for disposal in EU **C.1.6 Exports from EU of processing waste** C.1.7 Output from the value chain
D.1.1 Production of manufactured products in EU sent to use in EU D.1.2 Exports from EU of manufactured products **D.1.3 Imports to EU of processed material** D.1.4 Manufacture waste in EU sent for disposal in EU

D.1.5 Manufacture waste in EU sent for reprocessing in EU **D.1.6 Exports from EU of manufacture waste** D.1.7 Output from the value chain
E.1.1 Stock of manufactured products in use in EU E.1.2 Stock of manufactured products at end of life that are kept by users in EU E.1.3 Exports from EU of manufactured products for reuse **E.1.4 Imports to EU of manufactured products** E.1.5 In use dissipation in EU **E.1.6 Products at end of life in EU collected for treatment** E.1.7 Annual addition to in-use stock of manufactured products in EU E.1.8 Annual addition to end-of life stock of manufactured products at end of life that are kept by users in EU
F.1.1 Exports from EU of manufactured products at end of life **F.1.2 Imports to EU of manufactured products at end of life** F.1.3 Manufactured products at end of life in EU sent for disposal in EU **F.1.4 Manufactured products at end of life in EU sent for recycling in EU** F.1.5 Stock in landfill in EU F.1.6 Annual addition to stock in landfill in EU
G.1.1 Production of secondary material from post-consumer functional recycling in EU sent to processing in EU **G.1.2 Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU** **G.1.3 Exports from EU of secondary material from post-consumer recycling** G.1.4 Production of secondary material from post-consumer non-functional recycling G.1.5 Recycling waste in EU sent for disposal in EU

Figure A1. Flow chart of the MSA presenting the flow and stock parameters



Source: (BIO by Deloitte, 2015).

Annex 5. Mapping of EU-funded R&I projects and networks addressing bauxite residue valorisation

Acronym	Objective with relation to bauxite residues	Duration	Funding Scheme	Budget (EU contribution) in EUR millions	Project website/online reference
RemovAL Removing the waste streams from the primary Aluminium production	Combine, optimize and scale-up existing processing technologies (e.g., EAF processing for iron production, hydrometallurgical leaching for REE/Sc, slag valorisation) to achieve viable processing of bauxite residues and spent pot lining, while generating revenue through the extraction of base and critical metals and valorising the remaining processing residues in the construction sector	2018-2022	H2020	11.48 (11.48)	https://www.removal-project.com/ https://cordis.europa.eu/project/id/776469
ReActiv Industrial Residue Activation for sustainable cement production	Create a novel sustainable symbiotic value chain, linking the by-product of the alumina production industry and the cement production industry.	2020 - 2024	H2020	10.54 (8.81)	https://reactivproject.eu/ https://cordis.europa.eu/project/id/958208
ENSUREAL Integrated cross-sectorial approach for environmentally sustainable and resource-efficient alumina production	Develop a zero-waste process (modified Pedersen process), for alumina production and valorised by-products such as cast-iron, fertilisers, soil improver and critical raw material concentrates (REE, Ga), capable of accepting lower grade ores than the existing Bayer process	2017-2022	H2020	8.99 (7.25)	https://www.ensureal.com/ https://cordis.europa.eu/project/id/767533
ENEXAL Novel technologies for enhanced energy and exergy efficiencies in primary aluminium production industry	Demonstrate the potential of novel technologies for the efficient reduction of alumina to aluminium and the complete utilisation of bauxite residues	2010-2014	FP7	8.47 (4.95)	http://www.labmet.ntua.gr/enexal/ https://cordis.europa.eu/project/id/249710
SCALE Production of Scandium compounds and Scandium Aluminium alloys from European metallurgical by-products	Develop and demonstrate a European scandium value chain through innovative technologies, starting from the extraction of scandium from industrial residues (bauxite residues and acid wastes from TiO_2 pigment production) and finishing to high tech end-product	2016-2020	H2020	7.71 (7.00)	https://cordis.europa.eu/project/rcn/206331_en.html
REDMUD European Training Network for Zero-waste Valorisation of Bauxite Residue (Red Mud)	Train researchers in the science and technology of bauxite residue valorisation, with emphasis on the recovery of Fe, Al, Ti and rare earths (incl. Sc) while valorising the residuals into building materials.	2014-2018	H2020	3.72 (3.72)	http://etn.redmud.org/ https://cordis.europa.eu/project/id/636876
RIS-ALiCE Al-rich industrial residues for mineral binders in ESEE region	Valorise Al-rich industrial and mine residues (steel slags, red mud, ashes, landfills of bauxite mines) by the synthesis of mineral binders with high Al content to be used as a construction material	2019-2021	EIT Raw Materials (H2020)	NA	https://eitrawmaterials.eu/project/ris-alice/ http://ris-alice.zag.si

BRAVO Bauxite residue and aluminium valorisation operations	Network under the European Innovation Partnership on raw materials for secondary raw materials recovery from the aluminium value chain	2014-2020	EIT Raw Materials (H2020)	NA	http://bravoeip.eu/ https://ec.europa.eu/growth/content/bravo-bauxite-residue-and-aluminium-valorisation-operations_en
MUD2METAL Recovery of Critical Metals from the Bauxite Residues (red mud) of the primary alumina refining industry	Network under the European Innovation Partnership on raw materials for developing both the fundamental knowledge and the applied technology for recovery of metals from bauxite residues	2014—2020	EIT Raw Materials (H2020)	NA	https://ec.europa.eu/growth/content/recovery-critical-metals-bauxite-residues-red-mud-primary-alumina-refining-industry_en

Source: JRC elaboration

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