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Decarbonisation Options for the Aluminium Industry

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Contents

Abstract

The aluminium industry plays an important part in the EU economy, not only for its intrinsic value, but also as a link in the chain of other industries. This report provides an overview of the decarbonisation technologies available to the industry to enable it to fulfil its contribution to the EU's 2030 and 2050 decarbonisation goals. Electrification from RES as well as three key technologies are identified with the potential to decarbonise the aluminium industry. Direct electrification of processes is an integral part of the decarbonisation, compounded by the ambition to decarbonize electricity generation in the EU Carbon capture is the most developed of these, on the verge of break-even price for this industry. Hydrogen can be used to replace fossil fuels and reduce CO_2 emissions in high temperature applications. Inert anodes have the potential to eliminate smelting process emissions while increasing efficiency, thus lowering the industry's demand for power. The aluminium sector can become carbon-neutral, but economic and technological barriers remain. One option is to make more use of the secondary production route, which uses 95% less energy, but the economics of this are highly dependent on the availability of scrap. Around 30% of global carbon is currently subject to taxation, and this proportion is growing. As technologies mature and the price of CO_2 increases, the tipping point for industry-wide decarbonisation is coming closer.

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Zore, Lovro

Executive summary

The aluminium industry is important to the EU economy, while being responsible for around 0.3% of its CO_2 emissions (excluding alumina refining). The industry now faces the task of reducing its CO_2 emissions to be in line with the EU's climate targets while remaining competitive in a globalised industry. This report reviews the current state of the aluminium industry, both globally and domestically, and presents an overview of the technologies that are being developed and adopted to decarbonise the sector and the potential effects of their implementation.

Policy context

The EU has set clear ambitions for decarbonisation under the European Green Deal, with a target to reduce greenhouse gas (GHG) emissions by at least 55% by 2030 and reach climate-neutrality by 2050. In order to achieve these goals, all sectors will have to find ways of transforming their processes into non-emitting and sustainable activities.

The EU Emissions Trading System (ETS) provides a mechanism to increase innovation and cost-effectiveness under ever-stricter CO_2 emissions constraints within the EU. In order to level the playing field with third countries that do not impose any carbon costs on their industrial production, the Carbon Border Adjustment Mechanism (CBAM) was introduced in October 2023. CBAM functions by aligning the carbon cost of products imported into the EU with the carbon expenses borne by entities operating within the ETS framework. By doing so, CBAM eliminates the need for free allowances under ETS and thereby bolsters the impact of ETS in curbing CO_2 emissions and influencing price structures. Notably, the revenues generated through ETS will be directed towards offsetting these incurred expenses, particularly through initiatives like the Innovation Fund. The Innovation Fund is one of the world's largest funding programmes, designed to support the development of low-carbon technologies by facilitating the demonstration of decarbonisation solutions.

Main findings

The total emissions of the aluminium industry (from mining to secondary production) arise from direct process emissions (15%), thermal requirements (11%) and indirect emissions from power consumption (65%) and other sources (9%).

Carbon capture, utilisation and storage (CCUS) has the capacity to mitigate the emissions in the sector. Although it is attracting significant attention in a number of other industries, its application in the aluminium industry would have to be tailored, due to low flue gas concentrations (1-1.5% CO_2 concentration as compared to a coal power plant where it can be up to 13.5%). CCUS is cost-competitive in industries with higher CO_2 concentrations, but the price for the aluminium industry could become competitive in the years to come, with changes in carbon pricing and in the technology itself.

Another way of decarbonising the industry is through the use of hydrogen. Its main application is in high temperature processes, where fuel burning emits greenhouse gases. There are still some technological improvements to be made in the hydrogen production process to increase efficiency, but the greatest barrier to implementation is the cost of hydrogen produced with renewable energy sources.

Inert anodes are a potential game changer in the aluminium industry, but are not yet commercially available. Moreover, given the technology readiness level (TRL) of the technology (4-5), the cost is hard to estimate. Inert anodes could reduce almost all emissions arising from the smelting process and increase the smelting efficiency by 25%. Combined with other technologies they have the potential to almost completely eliminate CO_2 emissions from the industry.

Electrification of certain thermal processes is possible, given that the technologies exist, but the recent volatility of electricity prices and the high capital investment reduce the willingness of immediate implementation.

The secondary production route offers huge energy savings (95%) as compared to the primary route, but the quantities are driven by the availability and prices of scrap, latter of which is driven by the price of primary-sourced aluminium, and the cost of recycling.

Electrification of low and mid temperature applications, as well as other processes is an integral part of the decarbonisation. It is further compounded by the goals of making the EU power sector completely renewable.

Other improvements in the aluminium production process exist (such as waste heat recovery, low-temperature digestion, low electrolysis temperature and carbothermic reduction of alumina), with varying degrees of reduction capacity and cost, but their effects are hard to quantify given their bespoke nature, depending on facility layout, the processes implemented, co-dependence and other factors.

Key conclusions

The aluminium sector can become carbon-neutral, but economic and technological barriers remain. Carbon costs have previously been circumvented by outsourcing production to countries with less rigorous environmental standards (no emission standards, no trading schemes, no reporting requirements, no carbon tax, etc). The main barrier for the implementation of most technologies is the cost, i.e. the cost of CO_2 reduction is higher than the cost of CO_2. Around 30% of global carbon is currently subject to taxation, and this proportion is growing. As technologies mature and the price of CO_2 increases, the tipping point for industry-wide decarbonisation is coming closer. The EU aluminium industry is at a crossroads, but well placed to start implementing decarbonisation technologies, improving the industry's environmental impact and its competitiveness.

Related and future JRC work

JRC publications JRC 125390 "Sustainability aspects of Bauxite and Aluminium", JRC127468, "Technologies to decarbonise the EU steel industry", JRC131246, "Decarbonisation options for the cement industry", analysed their respective industries, providing insights into decarbonisation challenges and opportunities pertaining to the EU. The publication JRC96680, "Energy Efficiency and GHG Emissions: Prospective Scenarios for the Aluminium Industry", performed scenario analysis of the implementation of best available techniques to address GHG emissions. This report serves as a continuation and expansion of the work in those reports.

1 Introduction

Aluminium is the world's most used non-ferrous metal (NFM). The aluminium industry is a major sector of the EU economy, with an annual turnover of EUR 40 billion in 2018 (European Aluminium, 2023a). Aluminium's value to the EU lies not only in its production value, but also as a crucial input to many other EU industries, such as the automotive industry, construction, packaging industry, aerospace and energy transport. Total primary aluminium production in 2022 in EU27 was 1.92 million tonnes from 11 facilities (European Aluminium, 2023b), with direct emissions of around 2.75 million tonnes of CO_2e (European Environment Agency, 2023b). The EU has set ambitious goals to reduce emissions by 55% by 2030 and to become the first climate-neutral continent by 2050 (European Commission, 2021b). This obliges the sector to align its production and emissions with the EU's climate targets while remaining globally competitive.

This report provides an overview of the decarbonisation technologies available to the aluminium industry, along with their technological readiness levels (TRLs), overview of the potential cost of their implementation and their effect on greenhouse gas reduction.

Chapter 2 presents the energy- and emissions-intensity of the aluminium industry and its significance. This serves to illustrate the scale of the decarbonisation challenge.

Chapter 3 offers an insight into the aluminium sector, who the world's main producers are and where the EU fits on a global scale. It explores the EU's possible dependence on bauxite and alumina crucial for aluminium production. It also provides data on the efficiency of EU production and its total emissions to understand how much the aluminium industry contributes to greenhouse emissions and how much could be reduced. It is important to understand the origin of the emissions, so the production processes are explained in detail in chapters 3.1.1, 3.1.2 and 3.1.3 on alumina production, primary and secondary production. Every production step has different processes, different emissions and different decarbonisation challenges.

Chapter 4 provides a detailed overview of decarbonisation technologies currently available and in development. It assesses their (potential) impact on emissions and the cost of their implementation. Given that some technologies are already available in other industries, or are in development, the TRL will be provided. This gives indication how far from implementation and utilisation given technologies are.

These chapters are then synthesised in chapter 5, where an overview is given of the effect and cost of decarbonisation. This provides insights into the industry's capacity for decarbonisation and the extent to which a price gap is present, i.e. the gap between the incentive for decarbonisation (carbon price) and the price of decarbonisation (carbon reduction cost).

The conclusions highlight the barriers and prospects of decarbonising the aluminium industry, offering a sense of what it will take to meet the industry's climate neutrality obligations.

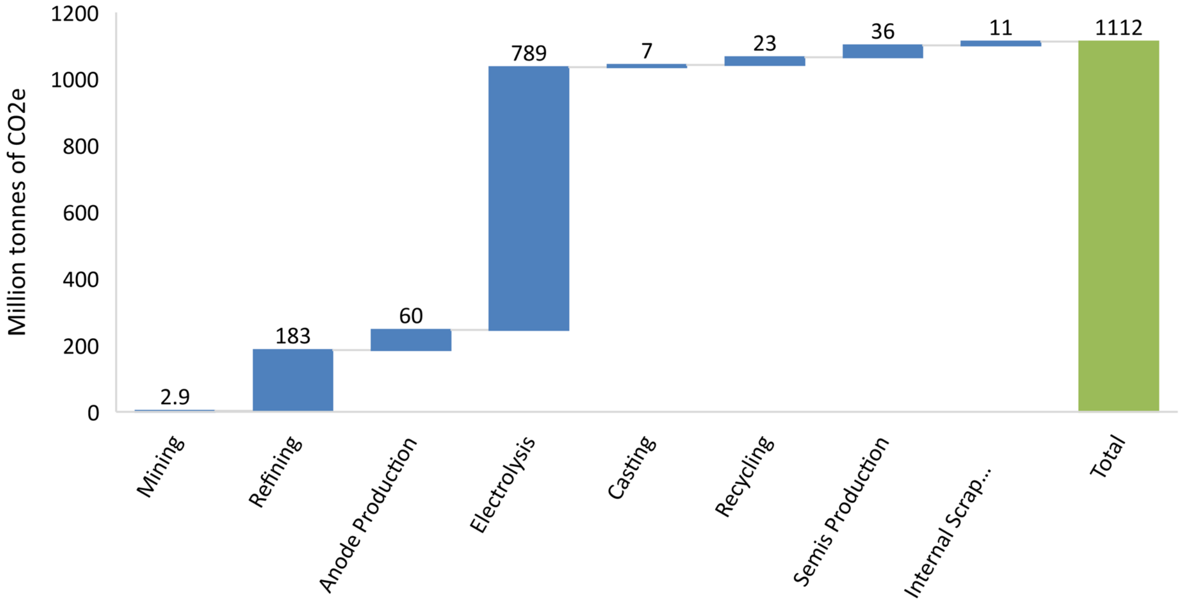
2 Aluminium decarbonisation challenge

As one of the more energy-intensive industries, representing 1% of EU27 total industry consumption in 2018 (Eurostat, 2020) and 3% of the world's direct industrial CO_2 emissions in 2022 (International Energy Agency, 2023), the aluminium sector faces significant pressure to align with EU climate goals and reduce its environmental impact. Factors which contribute to the challenge of decarbonising the aluminium industry are: process energy intensity, carbon intensive feedstock alumina, electricity carbon intensity and use of carbon anodes (which emit CO_2 in the reduction reaction and cause the release of PFCs). The industry encompasses a wide range of activities from mining and refining raw materials to producing finished aluminium.

Aluminium production is characterised by high energy consumption, primarily during the smelting process. Globally, around 13.2 MWh was used per tonne of primary aluminium in 2022 (International Aluminium, 2023f) and 2.8 GJ per tonne of anode. On top of that, the global energy intensity of alumina refining is around 10.2 GJ per tonne of alumina (International Aluminium, 2023b), or 20.4 GJ per tonne of primary aluminium, since 1.92 tonnes of alumina are needed per tonne of primary aluminium (more on that in chapter 3.1.2) (European Aluminium, 2018). The traditional Hall-Héroult process, used to extract aluminium from alumina, relies on large amounts of electricity, more specifically around 14.1 MWh globally, 15.5 in Europe. The carbon intensity of EU27 power is around 238 g of CO_2 per kWh (European Environment Agency, 2023a). In theory, this means the release of 3.7 tonnes of indirect emissions of CO_2 per tonne of primary aluminium. In practice, this figure is lower because the aluminium smelters use a power mix more favourable towards hydro, as shown in chapter 3.1.2, lowering the indirect carbon intensity of primary aluminium production.

The majority of emissions (71%) in the aluminium industry globally are from the electrolysis step, out of which, 78% are from indirect emissions (International Aluminium, 2023e). The total emissions of the global aluminium industry are shown in the image below.

Figure 1. Global $CO2_e$ emissions of the aluminium industry in 2022 (million tonnes).



Source: JRC based on (International Aluminium, 2023e)

The electrolytic reduction of alumina releases carbon dioxide as a result of the process. The industry is actively seeking ways to minimise or eliminate these emissions, and emissions from upstream processes, while maintaining cost-effectiveness and operational efficiency.

The industry operates in a competitive global market. Transitioning to low-carbon technologies and processes requires significant investment in research, development and infrastructure. Balancing the economic viability of these changes with environmental goals is a critical challenge.

Developing and implementing new technologies, such as advanced electrolysis methods (super-high amperage potlines and inert anode smelter such as the Elysis electrolysis cell (Tabereaux, 2019)), carbon capture and utilisation, and renewable energy sources, is essential for achieving deep decarbonisation. However, scaling up and integrating these technologies into existing operations presents technical and logistical challenges.

While recycling aluminium reduces energy consumption and emissions compared to primary production (Wallace, 2011), challenges remain in optimising the collection, sorting and processing methods. Increasing recycling rates requires coordination among various stakeholders, including consumers, manufacturers and waste management systems (Kumar, 2023). The profitability of recycling is also dependent on market conditions. The recycling aspect of the aluminium industry is further developed in section 3.1.3 of this report.

Ultimately, the aluminium industry's success in overcoming the decarbonisation challenge will contribute not only to its own environmental impact but also to global efforts to combat climate change and create a more sustainable future.

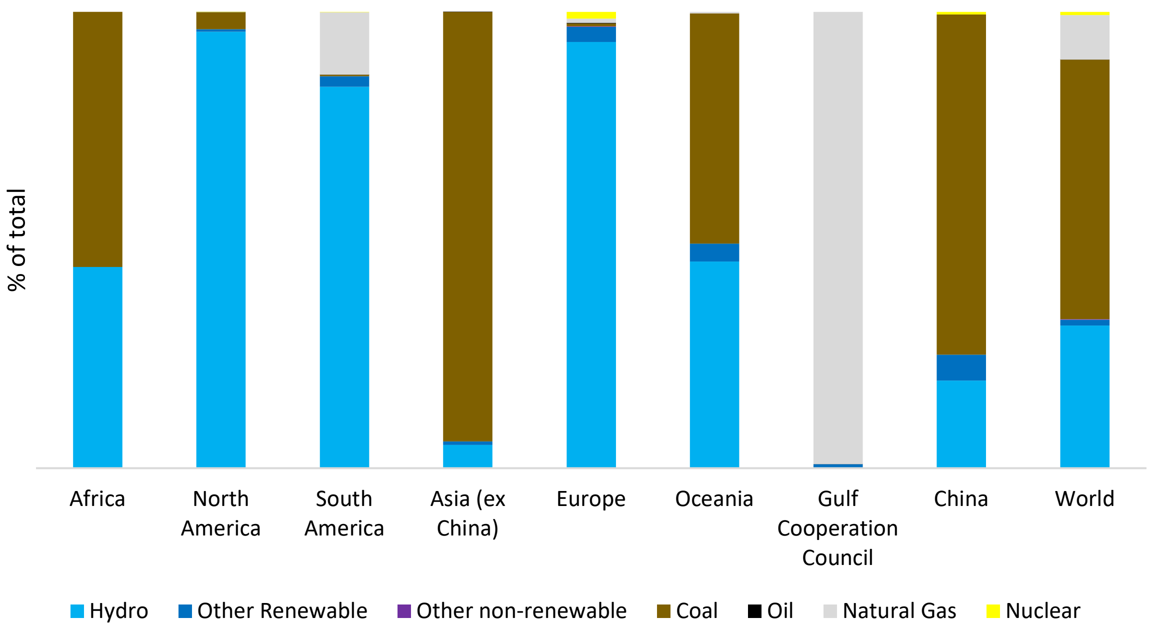
3 Aluminium sector today

The aluminium sector is a global industry that plays a crucial role in various aspects of modern life such as the beverage and packaging industry, car manufacturing, household appliances and aviation. It encompasses a range of activities from mining and refining raw materials to producing finished aluminium.

Sustainability has become a central focus in global politics as well as in industry (United Nations, 2023a). As environmental concerns and the need to reduce carbon emissions have gained prominence, the industry has been actively working to minimise its environmental footprint. This includes efforts to reduce energy consumption, adopt cleaner production methods and increase the recycling of aluminium products.

Renewable energy sources are being integrated into aluminium production processes to reduce the sector's impact on the environment. Solar, wind, hydroelectric and geothermal power are being harnessed to provide cleaner energy for smelting and refining processes, thereby reducing greenhouse gas emissions associated with traditional energy sources. The power mix and the total electricity consumption is given in Figure 2 and Figure 3 (International Aluminium, 2023d).

Figure 2. Fuel mix of power consumed in aluminium smelters in 2022[1].



Source: JRC based on (International Aluminium, 2023d)

The amount of total electricity consumed is linked to the volume of production, with China being the single largest producer of primary aluminium and aluminium products, responsible for 540 TWh consumed for the production of primary aluminium, followed by Europe (119 TWh), Gulf countries (90 TWh) and North America (49 TWh).

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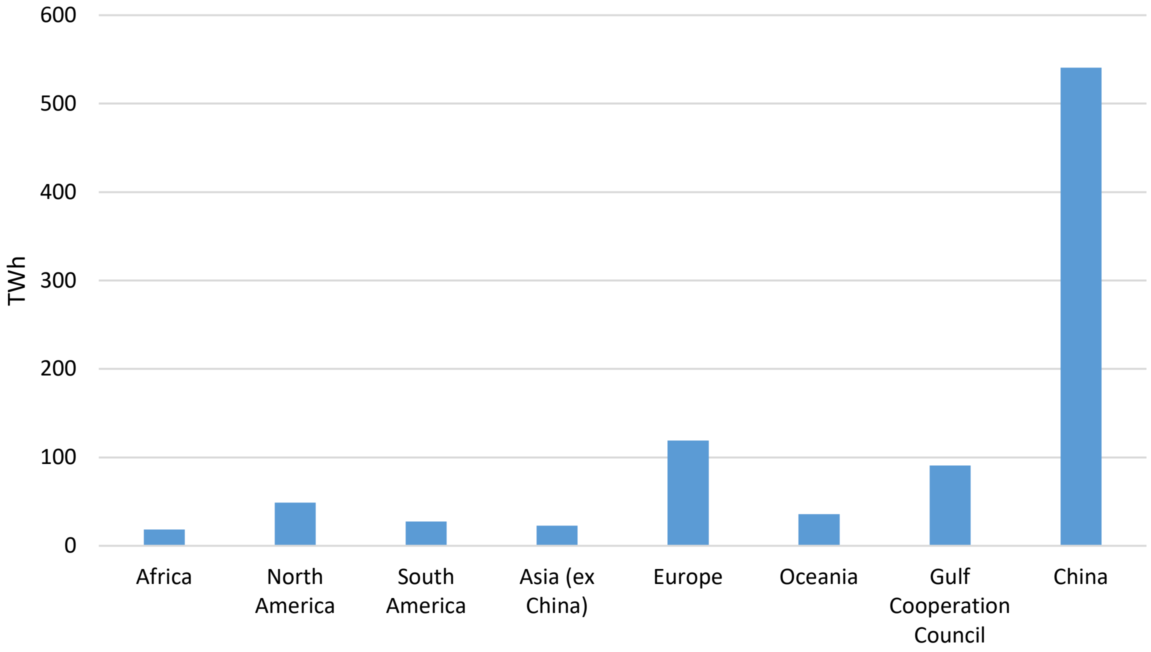
[1] Africa: Cameroon, Egypt, Ghana, Mozambique , Nigeria and South Africa
North America: Canada and United States of America
South America: Argentina, Brazil, Mexico, Suriname and Venezuela
Asia (ex China): Azerbaijan, Bahrain, India, Indonesia, Iran, Japan, Kazakhstan, Malaysia, North Korea, South Korea, Tadzhikistan, Taiwan, Turkey and United Arab Emirates
Europe consists both out of EU27 and non-EU countries. Countries in scope are: Austria, Bosnia and Herzegovina, Croatia, France, Germany, Greece, Hungary, Iceland, Italy, Montenegro, Netherlands, Norway, Poland, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine and United Kingdom
Oceania: Australia and New Zealand
Gulf Cooperation Council: Bahrain, Oman, Qatar and United Arab Emirates

Figure 3. Electricity consumption in primary aluminium production in 2022[2].



Source: JRC based on (International Aluminium, 2023d)

As can be seen from Figure 2, the global energy mix of the power consumed in the aluminium smelters is heavily dependent on hydrocarbons. Coal accounts for 56.9% of the total energy mix, followed by hydropower accounting for 31.3% and natural gas accounting for 9.7%. The three account for 97.8% of the energy mix in 2022 (International Aluminium, 2023d).

In Europe, the ratio of the electricity power mix is more favourable towards hydropower, which accounts for 93.4% of the energy mix in 2022, followed by renewables at 3.3%, nuclear at 1.5%, natural gas at 0.9%, coal at 0.7%, oil at 0.2% and other non-renewables at 0.1%. (International Aluminium, 2023d)

In terms of absolute electricity consumption for primary aluminium smelting, Europe (EU27 + Russia + EFTA) is ranked second after China with 119 TWh consumption in 2022 (International Aluminium, 2023d).

Recycling is another key aspect of the aluminium sector's sustainability efforts. Aluminium is highly recyclable without any loss of quality, and recycling helps conserve energy and natural resources. This focus on circular economy principles involves collecting and reprocessing post-consumer scrap to create new products, reducing the demand for primary aluminium production. In Europe, around 5 551 tonnes of aluminium were recycled in 2021. Out of that, 30.7% was new scrap, while 69.3% was post-consumer scrap (International Aluminium, 2023a). Recycled aluminium accounts for 60.3% of produced raw aluminium in Europe. Recycling rates in the automotive and building sectors are over 90%, while aluminium beverage cans have a recycling rate of 76%. Europe has the highest recycling efficiency rate (RER) of any region in the world, recycling 81% of the aluminium scrap potentially available in the region (International Aluminium, 2020a).

Technological advancements have significantly transformed the sector, improving energy efficiency and reducing emissions, particularly of PFCs (International Aluminium, 2019). Innovative production methods, such

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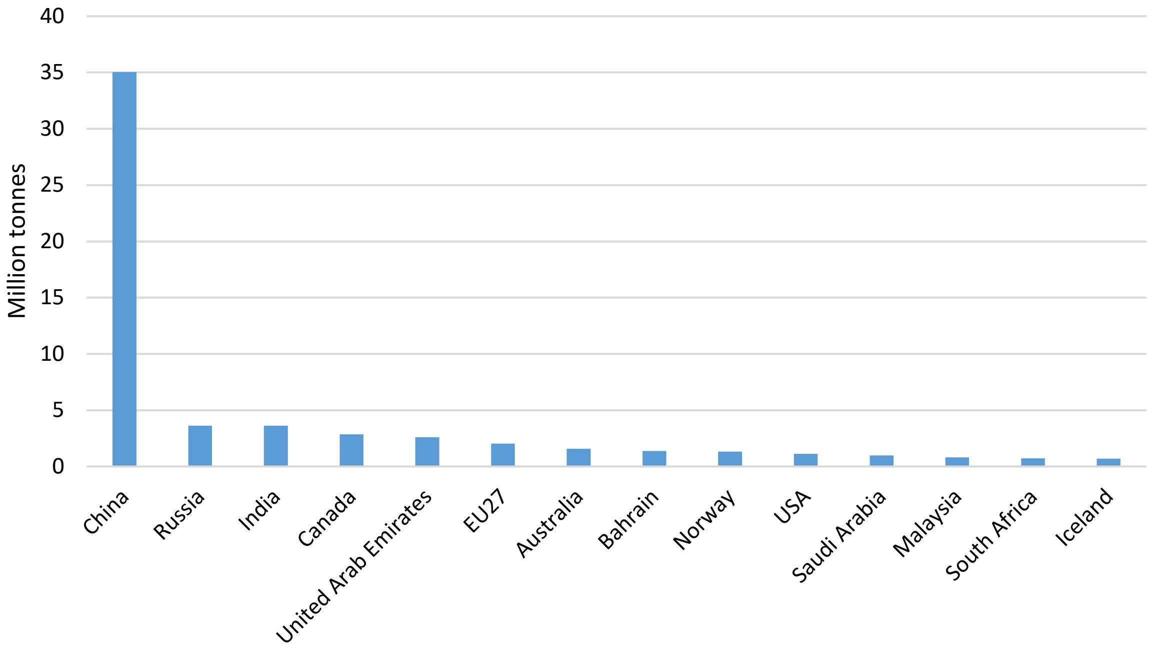
[2] Africa: Cameroon, Egypt, Ghana, Mozambique , Nigeria and South Africa
North America: Canada and United States of America
South America: Argentina, Brazil, Mexico, Suriname and Venezuela
Asia (ex China): Azerbaijan, Bahrain, India, Indonesia, Iran, Japan, Kazakhstan, Malaysia, North Korea, South Korea, Tadzhikistan, Taiwan, Turkey and United Arab Emirates
Europe consists both out of EU27 and non-EU countries. Countries in scope are: Austria, Bosnia and Herzegovina, Croatia, France, Germany, Greece, Hungary, Iceland, Italy, Montenegro, Netherlands, Norway, Poland, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine and United Kingdom
Oceania: Australia and New Zealand
Gulf Cooperation Council: Bahrain, Oman, Qatar and United Arab Emirates

as the development of advanced cell technologies and efficient recycling techniques (such as modern point-fed prebake smelters and modern point-fed prebake without fully automated anode effect intervention strategies for PFC emissions smelters), have improved energy efficiency and overall sustainability. These advancements also contribute to the sector's ability to adapt to changing market demands and customer shift, i.e. from more industrial uses to consumer products. The reductions have been significant – in 1995, the PFC emissions from aluminium totalled around 73 million t CO_2e, halved to around 35 million t CO_2e in 2019. Meanwhile, production rose from 20 million tonnes of primary aluminium in 1995 to 63 million tonnes in 2019. In other words, the emission intensity from PFCs decreased from 3.65 t CO_2e in 1995 to 0.56 t CO_2e in 2019 (International Aluminium, 2019).

Global supply and demand dynamics, along with market trends, influence the aluminium sector's landscape. Major aluminium-producing countries and regions, like China, Russia, Australia, and the Middle East (production shown in Figure 4), have a significant impact on production levels and pricing. Additionally, material demand and the industry's engagement with regulatory frameworks, international trade policies and economic conditions shapes its overall increasing demand trajectory.

Figure 4. Production of primary aluminium in 2019.



Source: JRC based on (British Geological Survey, 2023)

In summary, the aluminium sector today is characterised by sustainability initiatives, technological innovation and global market integration. As society continues to prioritise environmental responsibility, the sector's emphasis on cleaner production methods, energy efficiency and recycling will remain integral to its evolution.

3.1 Aluminium production

Aluminium is the third most abundant element in the earth’s crust, and the most abundant metallic element. For the last 50 years, it has been second only to iron in its industrial use. Aluminium does not occur in an elemental state; rather it is always combined in a chemical compound. The characteristics of aluminium are that it is light (1/3 the density of steel), it has a high electric and thermal conductivity, excellent corrosion resistance, high recyclability rates and a long lifecycle. Due to its excellent mechanical properties it has found its way into many areas such as machinery, transportation, containers & packaging, building & construction, consumer durables and electrical.

Primary aluminium production starts with the production of aluminium oxide (alumina) from the aluminium mineral (bauxite) and the conversion of aluminium oxide into elemental aluminium through the electrolytic process. An efficient method of extraction of alumina from bauxite was developed by Karl Joseph Bayer in 1888, while the development of the present electrolytic process occurred almost simultaneously in 1886 by

Charles Martin Hall in the United States and Paul L.T. Héroult of France (i.e. the Hall–Héroult process) (Lumley, 2011).

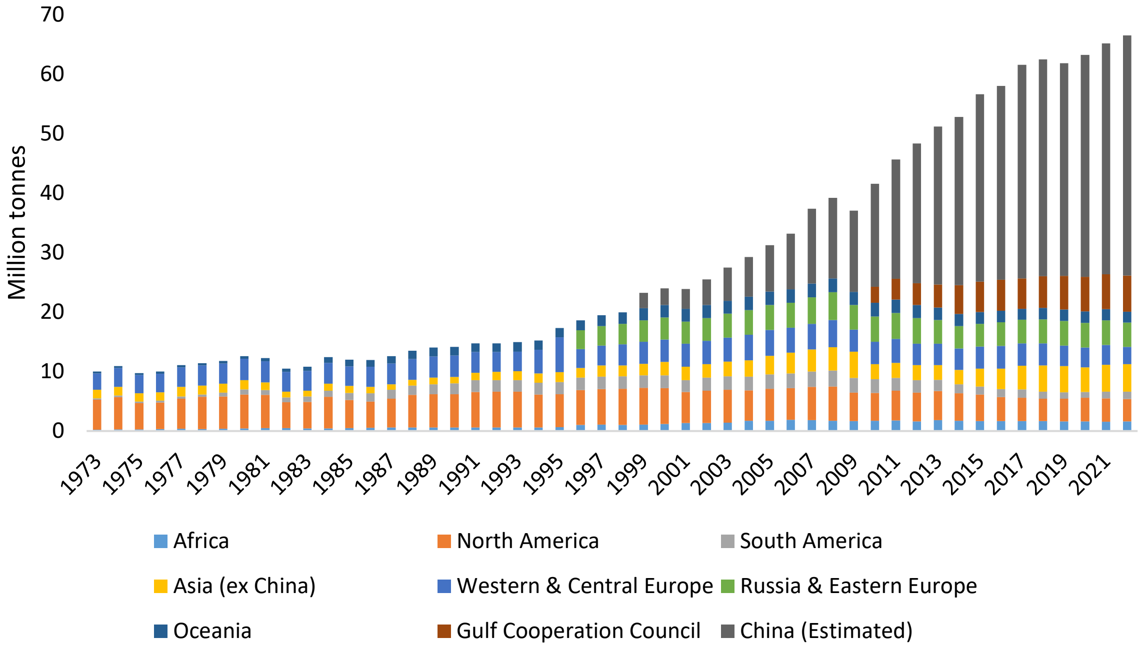
The primary ore of relevance to the aluminium industry is bauxite, a mixture of aluminium hydroxides and oxyhydroxides, accompanied by varying amounts of iron oxides, silicates and other impurities.

Primary aluminium is produced in electrolysis plants or smelters by the Hall-Héroult process. The carbon anodes are consumed in the electrolytic process (Kvande, 2011). The carbon anodes can be produced in a separate anode plant ('prebaked') or in the smelter using the Söderberg technology. In the EU, practically all carbon anodes are 'prebaked' (with the exception of Spain).

Secondary aluminium production uses scrap either in remelters or in refineries to produce recycled aluminium. Remelters use new scrap (also called process scrap or pre-consumer scrap) whereas refiners use old scrap (also called post-consumer scrap). Refiners produce casting alloy and remelters generate wrought alloys for sheet (foil), rolling and extrusion.

In general, four tonnes of bauxite are required to produce two tonnes of alumina, which are required to produce one tonne of primary aluminium. Global aluminium production has risen drastically in the past century – from 6 800 tonnes in 1900 to 100 000 tonnes in 1916, 1 million tonnes in 1941, 10 million tonnes in 1970 and 63 million tonnes in 2019. Global production data from 1973 onwards is shown in Figure 5 (Kvande, 2011).

Figure 5. Global production of primary aluminium per region in million tonnes.



Source: JRC based on (International Aluminium, 2023c)

3.1.1 Production of alumina

Aluminium exists in nature as a form of oxides, hydroxides and aluminosilicates. A large number of aluminium forms of the stoichiometry Al_2O_3 oxide are known. The most commercially exploited mineral forms are gibbsite ($Al(OH)_2$) and boehmite (AlOOH). Furthermore, transitional aluminas exist. The transitional aluminas are thermodynamically unstable, but play a role in production of specific aluminium grades. The primary ore in aluminium production is bauxite – a mixture of aluminium hydroxides and oxyhydroxides, iron oxides, silicates and other impurities. It was first documented in 1821 by Pierre Bertier, in his description of red-brown deposits near the village Les Baux-de-Provence, in Provence, France. The name originates from the name of the village. The most commercially exploited form of bauxite is tropical silicate bauxites, which are formed at the surface of various silicate rock formations such as shales, clays, granites and basalts. Given the mechanism of their formation, they are found around equatorial areas. Warm and mildly acidic rainfall leaches and alters primary metals, gradually removing silicates. The largest bauxite deposits can be found in Australia, Brazil, Guinea, India, Guyana, Suriname and Venezuela. The estimated reserves are 50-70 billion tonnes, with Africa, Oceania and South and Central America accounting for over 77%. The ore is extracted in typical surface or sub-surface mining operations.

The pivotal step in alumina production was patented by Karl Bayer in 1887. Bayer discovered that gibbsite formed a more useful crystalline form in an alkaline solution than it did when neutralising acid solutions. Although other processes exist (Petersen process and nepheline sintering), the Bayer process has become the industry standard.

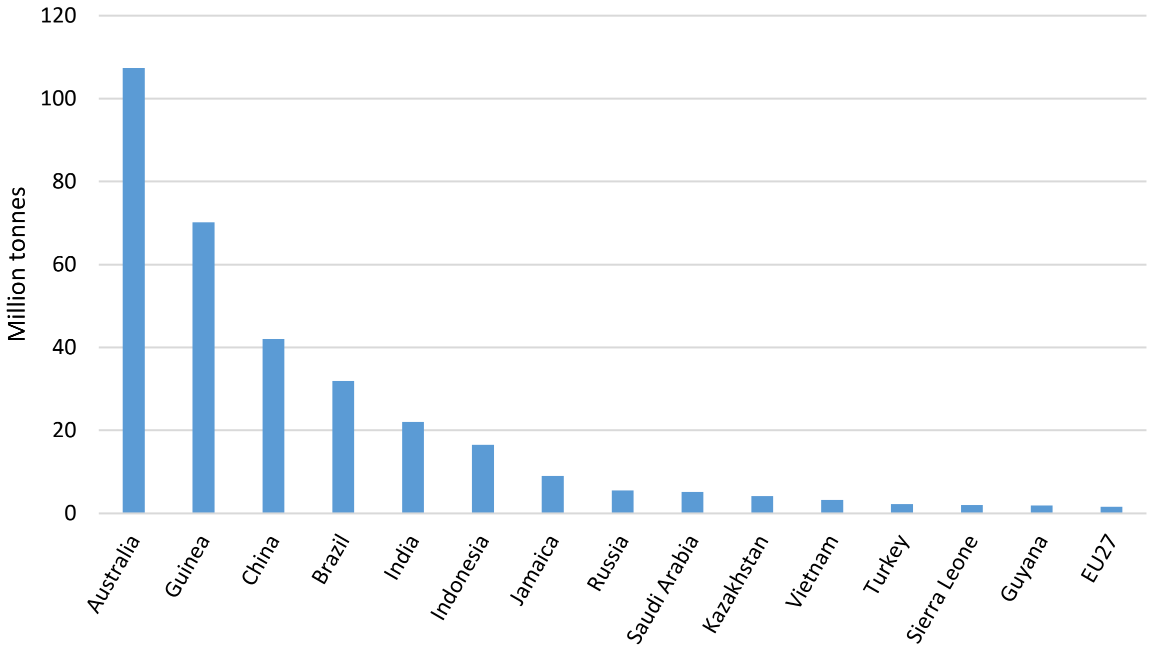
The Bayer process consists of four distinct steps:

1. Digestion
2. Clarification
3. Precipitation
4. Calcination

Alumina's main use is in producing aluminium metal, driven by increasing metal demand. The Bayer process dominates alumina production, with China's capacity growth leading to process variations for non-gibbsite type bauxites. Exhausted deposits and rising energy costs are a challenge, constrained by environmental concerns and operational issues. Projections link aluminium demand growth with GDP growth, suggesting a need for alumina capacity expansion. The location disparity between smelting and alumina production highlights the importance of refining global alumina standards and rethinking resource-inefficient production methods.

The total production of bauxite in 2019 amounted to 332 million tonnes, with the 10 largest producers accounting for 94.7% of total production, while the top three producers (Australia, Guinea and China) account for 2/3 of total production. The EU27 in its totality produced 1.6 million tonnes of bauxite in 2019, with Greece being the largest producer at 1.49 million tonnes of bauxite. Other EU producers are France and Croatia, producing 121 000 and 14 000 tonnes respectively. **Figure 6** shows the production distribution of bauxite (British Geological Survey, 2023).

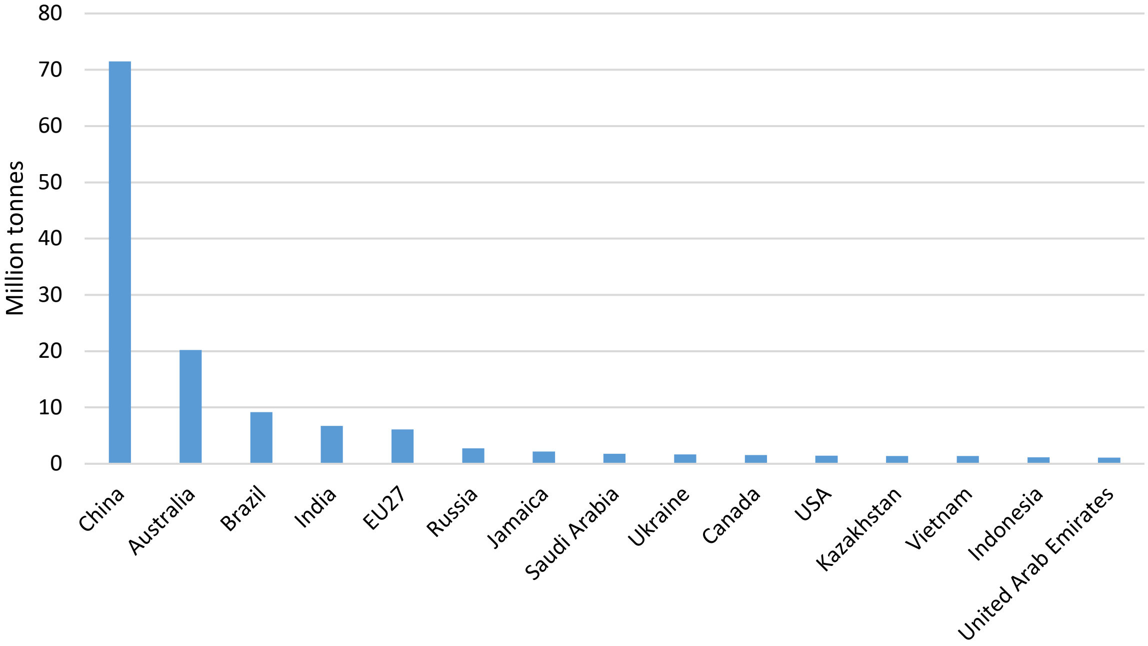
Figure 6. Production of bauxite in 2019.



Source: JRC based on (British Geological Survey, 2023)

As mentioned, roughly two tonnes of bauxite are needed to produce one tonne of alumina. In 2019, EU production amounted to 6 million tonnes of alumina. According to Comtrade (United Nations, 2023b) an import dependency for bauxite exists. The largest producer of alumina by far is China, accounting for 54% of the world's production (71.5 million tonnes out of 131 million tonnes), followed by Australia, Brazil and India. These countries account for 82% of total alumina production. The EU is the 5th largest alumina producer. The EU produced two million tonnes of primary aluminium in 2019, and according to Comtrade (United Nations, 2023b), the EU is a net exporter, which means there is enough alumina production in the EU to satisfy its demand.

Figure 7. Production of alumina in 2019.



Source: JRC based on (British Geological Survey, 2023)

The mining of bauxite and particularly of alumina are energy-intensive processes. Globally, bauxite mining consumes around 100 MJ of thermal energy and around 1.5 kWh of electricity per tonne of mined material. The energy is supplied from carbon-based fuels, such as heavy oil and diesel oil, which fuel the machinery required for bauxite extraction. The total thermal requirements for refining one tonne of alumina (globally) are around 12.3 GJ, with power requirements of around 200 kWh. This energy is sourced from carbon-based fuels, in particular coal (8 500 MJ), natural gas (2 600 MJ) and heavy oil (1 000 MJ). Including the emissions from carbons-based fuels, the process itself emits 0.47 kg of particulates, 1.14 kg of SO_2, 0.61 kg of NO_x, and 0.12 kg of mercury per tonne of refined alumina. These values are for 2015 (European Aluminium, 2018). Newer data suggests increased efficiency of around 10.2 GJ per tonne of alumina in 2022, but no more detail is given (International Aluminium, 2023b).

In 2019 the EU had only one bauxite producing country, with several mines - Greece, so the bulk of the mineral consumed in EU alumina refineries (10.5 million tonnes) has to be imported. The main trading partners over the 2016-2020 period were Guinea (accounting for 70% of the imports), Brazil (14%) and Sierra Leone (10%) (SCREEN, 2020).

3.1.1.1 Alumina refineries in the EU

In total, there are six alumina refineries in EU, five of which refine alumina for the production of primary aluminium and one produces exclusively special grades of alumina for non-metallurgical uses. The refineries are located in Ireland, Germany, France, Greece, Romania and Spain. The combined capacity of EU refineries is 5.29 million tonnes of alumina per year (5.89 if Tulcea in Romania reinstates its production capacity).

Figure 8. Location of EU alumina refineries.

Source: JRC based on (European Aluminium, 2023a)

Aughinish, Ireland

Rusal Aughinish Alumina, located in Ireland, stands as Europe's largest alumina refinery and is part of the UC RUSAL group. Established in 1978-1983, it was originally designed with an annual capacity of 800 000 tonnes of alumina. Over time, it has undergone significant expansions and technological upgrades, currently with an annual capacity over 1.9 million tonnes of alumina.

To meet its energy demands, Rusal Aughinish constructed a 160 megawatt Combined Heat & Power Plant (CHP Plant) onsite. This facility not only generates steam and power for the refinery but also supplies surplus electricity to the national power grid. Aughinish relies on natural gas as the primary fuel source, and its CHP Plant is the largest of its kind in both Ireland and the United Kingdom. As a result, Rusal Aughinish is one of the world's most energy-efficient high-temperature alumina refineries.

Furthermore, the refinery employs environmentally responsible practices for managing bauxite residue disposal in its Bauxite residue disposal area (BRDA). These practices include measures to protect the perimeter embankment from potential sea-level changes and to prevent residue from escaping into the surrounding areas. The use of Amphirol technology for mud farming is implemented to maximise compaction and storage capacity, while an automatic sprinkler system helps prevent fugitive dusting.

In 2019, the total capacity was 1.99 million tonnes of alumina, while the utilisation rate stood at 95%, producing a total of 1.89 million tonnes of alumina (World Aluminium, 2023).

Stade, Germany

Aluminium Oxid Stade GmbH (AOS), located in the Stade-Bützfleth industrial zone, was constructed during the years 1970 to 1973 and is situated on a 55-hectare (approximately 133-acre) site. Production operations commenced towards the end of 1973.

AOS has successfully raised its nominal production capacity from an initial 600 000 tonnes of alumina per year to a total exceeding 1 million tonnes annually. These improvements extend beyond increased production. Improvements in capacity and modernisation have also led to substantial reductions in emissions (DADCO, 2023).

San Ciprian, Spain

The San Ciprian alumina refinery is owned and operated by AWAC (Alumina & Chemicals), a joint venture between Alcoa and Alumina Limited. The refinery is located on the north-west coast of Spain, specifically in the town of San Ciprian, in the province of Lugo, Galicia, Spain. The refinery has an annual production capacity of 1.6 million tonnes of alumina. Bauxite is shipped to the San Ciprian refinery from Boké, Guinea. Approximately 70% of the alumina produced at San Ciprian is supplied to Alcoa's aluminum smelters in Spain. The remaining production is primarily sold as commodity hydrated alumina to European chemical manufacturers. The main energy source of the refinery is natural gas (Alumina Limited, 2023).

Gardanne, France

Alteo is a French industry whose head office is located between Marseille and Aix-en-Provence. Production primarily focuses on producing high-performance aluminas for various industrial applications, and it is not involved in the production of metallurgical-grade alumina (Alteo Alumina, 2023).

Tulcea, Romania

The Alum Tulcea refinery is located in the city of Tulcea and has a capacity of 600 000 tonnes of alumina per year. The alumina produced is almost exclusively supplied to the Alro Slatina aluminium facility. The smelter was shut down in June 2022 due to high energy prices (Alum, 2023).

Distomon, Greece

Mytilineos is the only vertically integrated bauxite, alumina and primary aluminium production unit in all of Europe, with privately owned port facilities and the largest electricity cogeneration unit. Together with Delphi Distomon, which is the second largest producer of bauxite in Greece and by extension in Europe, annual production capacity exceeds 1.2 million tonnes of bauxite from underground construction sites alone. The production capacity of alumina is around 860 000 tonnes (Mytilineos, 2023).

3.1.2 Production of primary aluminium

Primary aluminium production is preceded by two energy-intensive processes that convert bauxite ore into metal. The Bayer process extracts alumina from bauxite, while the Hall-Héroult process uses electrolytic reduction of alumina dissolved in a molten salt electrolyte, primarily cryolite, to produce molten aluminium.

In an alumina refinery, bauxite is transformed into aluminium oxide (alumina, Al_2O_3), the essential material for primary aluminium production. The Bayer process involves extracting alumina through high-temperature and pressure caustic digestion of crushed bauxite, followed by clarification, precipitation, washing, and calcination to obtain pure anhydrous alumina. Some aluminium producers operate or partially own alumina refineries, while others buy alumina on the market, sending it to aluminium smelters. Alumina resembles table salt, appearing as a white powder. With a melting point exceeding 2 050°C, it is chemically highly stable, contributing to the substantial energy requirement for aluminium production from alumina.

The Hall-Héroult process is the primary method used for the production of aluminium metal from alumina. This electrochemical process involves the reduction of alumina through electrolysis to obtain molten aluminium.

The main steps of the Hall-Héroult process are:

1. Electrolysis cell: the process takes place in an electrolytic cell, which consists of a large rectangular container made of steel lined with refractory materials to withstand high temperatures. The cell is divided into two compartments by a carbon lining called the "cell cathode."
2. Electrolyte: the electrolyte used in the process is a molten salt mixture, mainly composed of cryolite (Na_3AlF_6) and aluminium fluoride (AlF_3). This mixture reduces the melting point of alumina, making the process more energy-efficient.
3. Anodes and cathodes: carbon blocks, which act as anodes, are suspended above the cell cathode. Alumina is fed into the cell and settles on the cell cathode. As the alumina melts, it dissolves in the electrolyte. The carbon anodes and the alumina-laden electrolyte create a conductive environment for the electrolysis to occur.
4. Electrolysis: when an electric current is passed through the cell, electrolysis takes place. At the anode (carbon), oxygen ions from the alumina combine with carbon to form carbon dioxide gas:
   $2Al_2O_3 \rightarrow 4Al^{3+} + 6O^{2-}$ $\quad$ $3C + 3O^{2-} \rightarrow 3CO_2 + 6e^-$

   At the cathode (cell lining), aluminium ions from the alumina gain electrons and form molten aluminium:
   $4Al^{3+} + 12^{e-} \rightarrow 4Al$ (molten)
5. Molten aluminium collection: The heavier molten aluminium sinks to the bottom of the cell and is periodically siphoned off. The molten aluminium is then transported and cast into various shapes for further processing.

The Hall-Héroult process is energy-intensive due to the need to supply a significant amount of electrical energy to sustain the electrolysis (up to 600 kA (Gupta & Basu, 2019)). However, it is a crucial method for producing aluminium on a large scale and plays a fundamental role in various industries. The process was independently developed by Charles Martin Hall and Paul Herold in the late 19th century and remains a cornerstone of modern aluminium production (Kvande, 2011).

The theoretical consumption is 1.89 tonnes of Al_2O_3 per tonne of produced aluminium, resulting in a reaction with 0.33 tonnes of carbon to yield 1.22 tonnes of carbon dioxide. However, in practice, typical values are slightly higher, around 1.92 tonnes of Al_2O_3 per kg of aluminium and 0.40-0.45 tonnes of carbon per tonne of aluminium. This practical ratio generates approximately 1.5 tonnes of carbon dioxide (Kvande, 2011). According to the European Aluminium Environmental Report, the amount of consumed carbon in Europe (EU27 + UK + EFTA) is 0.435 kg per kg of primary aluminium (European Aluminium, 2018). Reducing aluminium oxide to aluminium requires significant energy and high temperatures. This explains why aluminium became commercially available only about 150 years ago, while metals like iron, copper, bronze, and lead have been in use for thousands of years.

3.1.2.1 Carbon anodes

In the smelting step, carbon is a crucial component, as it is consumed in the anode reaction. Prebaked carbon anodes primarily consist of calcined petroleum coke obtained from heavy residual fractions of crude oil through delayed coking. This process upgrades oil refinery waste that would otherwise be low-value fuels. Anodes also contain around 13-16 wt. % coal tar pitch, which binds coke particles together. Pitch, a liquid hydrocarbon with over 90% carbon, comes from coal tar produced during coking of bituminous coal for steel. Anodes are prebaked in special furnaces before use. Carbon mass consumption has an efficiency of 70-80%. The described reaction has a standard Gibbs energy equivalent to 1.03 V, representing the standard electromotive force (emf) of a reversible fuel cell combusting carbon to CO_2. This accounts for the depolarisation attributed to the carbon anode. In current cells, approximately half of this energy is lost due to the overpotential at the carbon anode, resulting in 50% energy efficiency in carbon utilisation. Considering that the overpotential generates heat required to balance electrochemical process heat losses, the energy efficiency of the carbon anode reaches around 80%.

High-purity carbon is essential to avoid contaminating the aluminium or the electrolyte. Petroleum coke is a primary carbon source for anodes due to its purity. The structure varies based on petroleum feedstock and coking conditions. Calcination at about 1 200°C removes volatile elements and increases density. Crushed and sieved coke is blended with recycled anode material, mixed with pitch, moulded into blocks, and baked at 1 150-1 200°C to form carbon anodes. To provide support and electrical contact, aluminium or copper rods with iron yokes and stubs are attached to the anode.

Söderberg anodes are a type of consumable anode which differs from prebaked anodes. They consist of petroleum coke and pitch but contain more pitch (25-28 wt. %). Briquettes of Söderberg anode paste are baked by the electrolyte's waste heat, creating an electrically conducting composite that extends into the electrolyte. These anodes have higher electrical resistivity and are gradually replaced by prebaked anodes due to lower power efficiency and environmental challenges. In the EU27, only the San Ciprian smelter in Spain utilises Söderberg anodes (Kvande, 2011).

3.1.2.2 Electrolyte materials

In the electrolyte, cryolite generally makes up over 75% of the weight of the electrolyte, and additional components include excess aluminium fluoride (6-13%), calcium fluoride (4-7%) and alumina (2-4%). Lithium fluoride (2-4%) and magnesium fluoride (2-5%) can also be introduced as lithium carbonate and magnesium oxide. These additives serve to lower the melting point and operating temperature, leading to improved current efficiency.

Cryolite, a sodium and aluminium double fluoride mineral with a formula close to Na_3AlF_6, possesses a melting point of approximately 1 010°C. It was found predominantly in Greenland and was mined extensively there, but the mine's resources are now depleted. Synthetic cryolite can be generated by reacting hydrofluoric acid with alkaline sodium aluminate solution. Alternatively, cryolite can be recovered from used cell linings by dissolving fluorides with dilute sodium hydroxide solution, filtering, and then precipitating cryolite by neutralising the solution with carbon dioxide.

In reduction cells, cryolite can also be directly produced by the reaction of the soda impurity in feed alumina with added aluminium fluoride. Electrolyte generated this way needs to be periodically tapped from the cells. However, in modern smelters equipped with fume treatment and cells with lifespans exceeding 3 years, cryolite is now more of a by-product than a raw material in aluminium production.

Aluminium fluoride (AlF_3) can account for 12-13 wt. % of the electrolyte. Itis consumed through vaporisation and hydrolysis due to moisture, and is also depleted by reaction with soda present in the feed alumina.

Other additives like calcium fluoride and lithium fluoride have distinct effects on the electrolyte's properties. Calcium fluoride, typically originating from alumina impurities, has various impacts on temperature, vapour pressure, and solubility of reduced species. Lithium fluoride lowers the melting point and improves electrical conductivity, while magnesium fluoride can be added to expel carbon dust from the electrolyte (Kvande, 2011).

3.1.2.3 Cathode materials

The electrolyte and aluminium are housed within a preformed carbon lining enclosed in a steel shell, with refractory and thermally insulating materials incorporated. While anthracite has historically been a major component in the cell cathode blocks, graphitic and semi-graphitised materials are now commonly used. In the aluminium industry, the term "cathode" refers to the entire container of metal and electrolyte, although the true electrochemically active cathode is the upper surface of the molten aluminium pool (metal pad). Aluminium forms from aluminium-containing anions that are reduced at the interface between the electrolyte and the alumina/aluminium.

The materials employed consist of prebaked carbon cathode blocks, SiC (silicon carbide) sidewall bricks, and carbonaceous ramming paste. Manufacturers shape and bake cathode blocks and sidewall materials, while ramming paste is directly formed in the cathode through ramming and baked during cell preheating and operation.

To insulate the cathode, porous insulation bricks are used, which can be susceptible to electrolyte penetration. These insulation materials are safeguarded by using refractory bricks, and sometimes a barrier material made of steel and/or glass is introduced. Refractory bricks offer some insulation while keeping temperatures in the insulation materials within an acceptable range, striking a balance between insulation and protection.

Electric current deposits aluminium into a molten aluminium pool beneath the electrolyte within the carbon-lined cell cavity. Oxygen from alumina is electrolytically deposited onto the carbon anode immersed in the electrolyte and reacts with (burns) the anode.

Cells are typically sized between 9 and 14 m in length, 3 and 5 m in width, and 1 and 1.5 m in depth. However, the operating cavity's depth is only 0.4 to 0.5 m.

Thermal insulation encompasses the cell's carbon lining to manage heat losses. Even though carbon is best equipped to withstand the corrosive effects of molten fluorides and aluminium, it would have a limited lifespan in contact with electrolyte at the cell's sides if not protected by a layer of frozen electrolyte. The thermal insulation is precisely adjusted to maintain a protective coating on the sidewalls but not on the bottom, which must remain largely exposed for electrical contact. Steel collector bars in the carbon cathode conduct electric current from the cell, inserted into holes designed for tight electrical contact through thermal expansion or bonded in place with carbonaceous cement or cast iron (Kvande, 2011).

3.1.2.4 Electricity efficiency

Faraday's first law lays down that 1 kiloampere-hour (kAh) of electrical current should theoretically yield 0.335 kilograms of aluminium. However, in practice, the actual metal output ranges from 85% to 95% of this calculated quantity, a common phenomenon in electrolytic processes. To quantify these production losses and measure the electrochemical efficacy of the process, the concept of current efficiency (CE) is introduced. It is defined as the ratio of the observed production rate (p) to the theoretical production rate (po), expressed as a percentage:

$CE = (p / po) * 100\%$

In essence, current efficiency reflects the proportion of the current directed towards aluminium production, as per Faraday's law. The primary cause behind this loss in efficiency stems from the recombination of anodic and cathodic products. Reduced species dissolve into the electrolyte at the interface between aluminium and the electrolyte.

Although debate surrounds the exact nature of the dissolved species – whether it is metallic sodium, subvalent sodium, monovalent aluminium, colloidal aluminium, or a combination thereof – it is agreed that the occurrence of this dissolution impacts efficiency. Factors like the electronic conductivity of the melt can lead to lower current efficiency when a metal dissolves in a molten salt.

Minor efficiency losses arise from several mechanisms. For instance, new cell linings can absorb sodium, initially lowering current efficiency until saturation occurs. When metals dissolve in molten salt, they can increase electronic conductivity in the melt, further affecting efficiency. Elements such as phosphorus and vanadium, which experience partial reduction at the cathode and subsequent reoxidation at the anode, contribute to efficiency reduction.

The solubility of aluminium in industrial electrolytes is minimal, ranging from 0.03% to 0.06% by weight. Recent investigations propose that aluminium might dissolve in the form of AlF_2 ions:

$2\ Al\ (1) + Na_3AlF_6 \rightarrow 3\ AlF_2^- + 3\ Na^+$

This dissolved metal must diffuse through the metal-electrolyte boundary layer before being transported via convection to the anode region, where it can interact with carbon dioxide. While chemical reactions appear swift compared to mass transport, the controlling factor was previously considered to be the diffusion of dissolved metal at the metal-electrolyte boundary. However, recent findings suggest a mixed control scenario involving diffusion at both the aluminium-electrolyte interface and the bubble-electrolyte interface.

The intriguing question arises: how can negative ions (anions) participate in reactions at the negative cathode? Anions can indeed be reduced at the cathode if they contain an element with an oxidation state that can be lowered within the melt's stability range. Aluminium is such an element, and in the AlF2 species, it exists as a monovalent ion. Consequently, reactions leading to aluminium formation at the cathode can be represented as:

$AlF_4^- + 2e^- \rightarrow AlF_2^- + 2F^-$

$AlF_2^- + e^- \rightarrow Al\ (1) + 2F^-$

The specific energy consumption (EC), measured in kilowatt-hours per kilogram of aluminium produced, can be calculated using the following straightforward equation:

$EC\ (kWh/kg\ Al) = 2.9806 * V / CE$

In this equation, the current efficiency (CE) is provided as a fraction, and V represents the cell voltage measured in Volts. The concept of energy efficiency refers to the portion of the electrical energy introduced into the cell that is utilised for aluminium production. This electrical energy is the result of the product of the amperage and the voltage. Energy efficiency typically falls within the range of 45% to 50%, with the remaining portion of the energy input being converted to heat, which escapes from the cell into the surrounding environment.

Taking heat balance into consideration is crucial when designing and operating a cell at the optimal temperature. The calculation process is intricate due to the simultaneous occurrence of both heat flow and heat generation in conductors responsible for carrying electric current into and out of the cell. Interestingly, over half of the heat loss may transpire through the anodes and the upper crust of the cell. One notable aspect to emphasize is the necessity to safeguard the sidewalls from erosion by maintaining a ledge of frozen electrolyte, which is achieved by extracting just the right amount of heat required to achieve the desired thickness of the ledge. Given the intricate geometry and the intricate interplay between heat flow and electrical flow, it's often necessary to employ a computer programme that employs either a finite element or finite difference technique to accurately balance heat distribution (Kvande, 2011).

3.1.2.5 Perfluorocarbon gases

During the 1990s, the industry came to realise that perfluorocarbon gases formed during anode effects (primarily CF_4 and to a lesser extent C_2F_6) were potent and detrimental greenhouse gases. The anode effect refers to a situation where the normal electrochemical reactions at the carbon anode are disrupted or altered, leading to a decrease in current efficiency and an increase in energy consumption. During the anode effect, the anode voltage rises significantly, and various unwanted side reactions take place.

There are several causes of anode effects, including:

1. Accumulation of Impurities: Accumulation of impurities, such as metals or oxides, on the surface of the anode can interfere with the normal reaction and lead to reduced current efficiency.
2. Variations in Electrolyte Composition: Changes in the composition of the electrolyte, such as an excess of alumina or other impurities, can disrupt the anode reaction and trigger an anode effect.
3. Variations in Voltage: Rapid fluctuations in cell voltage, often due to operational changes, can induce anode effects.
4. Electrode Configuration: In Söderberg cells, where anodes are made in the own smelter from a paste-like mixture, variations in the paste composition can lead to localised anode effects.
5. Electrode Wear: Gradual wear of the anode surface over time can expose new areas of carbon, leading to local variations in reaction rates and potential anode effects.

When an anode effect occurs, the voltage across the cell increases significantly, inducing a drop in current efficiency. Undesirable side reactions can take place, including the formation of perfluorocarbon gases (CF_4 and C_2F_6), which are potent greenhouse gases. Anode effects result in energy wastage, increased emissions, and reduced aluminium production efficiency.

This was a shift from the earlier perception that these gases were benign, as they posed no harm to humans, animals, plants and the ozone layer, and their atmospheric presence was extremely low (5 million times lower than CO_2). In-depth research elucidated the mechanisms through which these gases emerged during anode effects in laboratory settings, and subsequent measurements in industrial cells provided data to quantify their emissions and compare results across various smelters.

However, a revelation by Marks et al. (2000) challenged previous assumptions. They proposed that low-level perfluorocarbon emissions might occur even without a formally defined anode effect, challenging the notion that these emissions were exclusive to anode effects (i.e., cell voltages exceeding 8 or 10 V). This discovery raises questions about whether the understanding of the phenomenon is exhaustive.

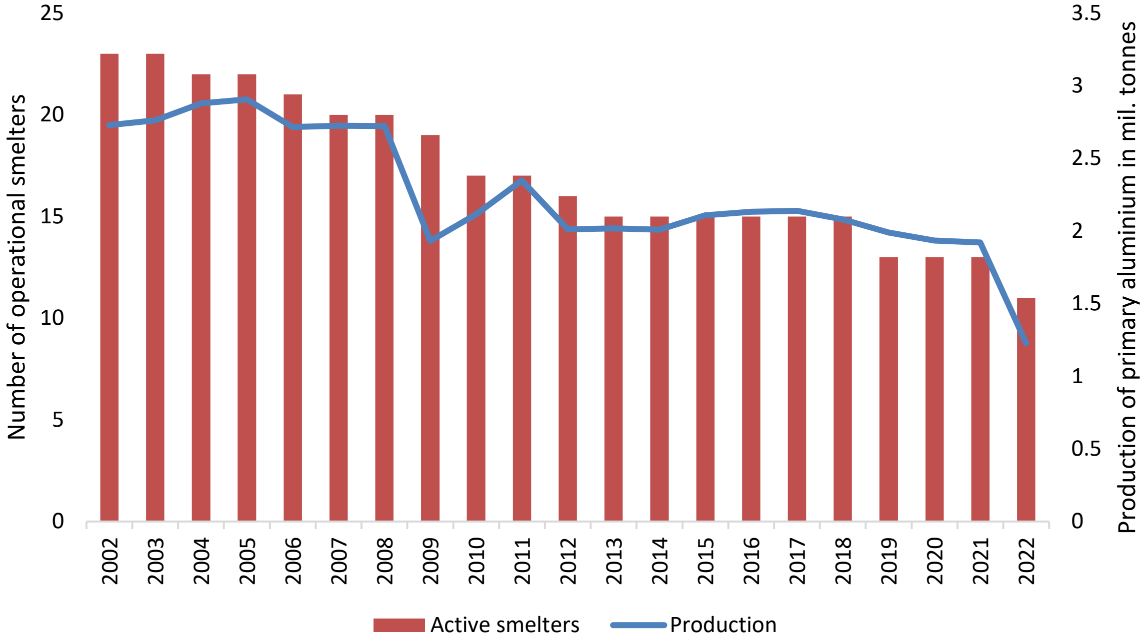
Efforts to reduce perfluorocarbon gas emissions have yielded positive outcomes in recent times, largely due to enhanced operational practices that led to a reduction in anode-effect instances. In modern prebake cells, extended operation without anode effects has become possible, with the ultimate aim being zero anode effects. As for Söderberg cells, pot lines are retrofitted to operate with prebake anodes, while newly built facilities utilise prebake technology exclusively. The potential exists for all cell types to function with fewer than 0.1 anode effects per cell-day, and the duration of anode effects can also be curtailed (Kvande, 2011).

IAI's survey (International Aluminium, 2020b) shows that over the years, significant progress has been made in curbing PFC emissions within the aluminium industry. With a remarkable reduction of nearly 90% in PFC emissions per tonne since 1990, coupled with a more than 200% growth in primary aluminium production during the same period, the absolute emissions of PFCs by the industry have dwindled from approximately 100 million tonnes of CO_2e in 1990 to 35 million tonnes in 2019 – a substantial decrease of 65%. However, the estimation of total emissions has shown an increase since 2009, primarily due to the expanding production of PFC-based products in China. This uptick carries an element of uncertainty due to the limited number of emission measurements (27 facilities) that form the basis for the average emissions in China. When examining the 1990 reporting cohort and comparing it with 2019 data, it is evident that improvements have been made by existing facilities over this time span, with the added positive impact of new capacity, predominantly in the form of PFC-based production, since 1990. Globally, PFC emissions (measured in CO_2e) per tonne of primary aluminium have decreased by nearly 40% since 2006 and almost 90% since 1990. Despite these advancements, the global PFC emission intensity has remained relatively stable since 2009, primarily due to China. This is because the emission intensity in China is based on an assumed average, given that the majority of PFC emissions originate from this region, aligned with its substantial aluminium production. Additionally, the average PFC emission intensity of the reporting cohort, which represents about three-quarters of global production excluding China, is approximately half of the modelled global emission intensity.

3.1.2.6 Primary aluminium smelters in the EU

In total, there are 10 primary smelters operating in the EU. Three are in Germany, two are in France and the others are in Greece, Spain, Slovenia, Slovakia and Sweden. The total production capacity of primary aluminium in EU is around 2.1 million tonnes per year. In the last twenty years the number of active smelters in the EU has halved, from 23 in 2002 to 11 in 2022, as can be seen in Figure 9. Consequently, the production of primary aluminium has also halved, from 2.7 million tonnes in 2002 to 1.2 million tonnes in 2022. The decline in production in 2022 can be due to other, external factors, such as the energy price crisis since autumn 2021 as well as supply and logistic shortages due to the COVID restrictions and the Russo-Ukrainian war, the latter of which had a profound impact on energy prices in the EU, especially on gas which has also had a major impact on electricity prices (ING, 2023).

Figure 9. Primary aluminium production quantity and number of active smelters in the EU.



Source: JRC based on (European Aluminium, 2023a)

Hamburg, Germany

In 2006, TRIMET took over a dormant electrolysis plant in Hamburg, marking a significant expansion of their production capacity. The plant was revitalised and resumed operation with a total of 270 electrolytic furnaces.

TRIMET resumed enhancing production efficiency which led to notable advancements in their processes. For instance, the modernisation of the anode furnace resulted in a substantial boost in annual production output, which now stands at 135 000 tonnes per year. Simultaneously, the company reduced specific energy consumption by over 40%.

The smelter set-up consists of 270 electrolytic furnaces housed within three production halls, all utilising the PBCWPF (pre-baked, centre-worked point feed) technology in a side-by-side configuration. The facility also features a casting carousel designed for handling aluminium sows. Furthermore, the plant is efficiently connected to a 110 kV power supply through a rectifier unit. Additionally, TRIMET operates an anode plant featuring an open ring furnace, with the production capacity of 120 000 tonnes of baked anodes per year. The electricity is supplied from a nuclear power plant by HE AG (Trimet, 2023).

Voerde, Germany

In May 2014, TRIMET acquired Voerde Aluminium GmbH. The Voerde plant comprises 188 electrolytic furnaces situated across two production halls. These employ the PBCWPF (Kaiser technology) anodes. To facilitate the handling of aluminium sows, the plant features a casting carousel, streamlining the production process. The plant is equipped with DC rectifier units connected to the supergrid, ensuring a consistent and efficient operation. The facility has an annual production capacity of 95 000 metric tonnes of primary aluminium per year. Additionally, the plant houses an anode plant equipped with an open ring furnace, with the capacity to produce up to 65 000 metric tonnes of baked anodes. The power is supplied by E.on (Trimet, 2023).

Essen, Germany

This is another TRIMET-owned smelter, featuring 360 electrolytic furnaces situated across three production halls, employing the PBPF cells in an end-to-end configuration. Complementing these are 12 gas-heated melting/holding furnaces, 12 induction-heated casting furnaces, and 4 melting/casting furnaces. Furthermore, the plant boasts 8 vertical continuous casters, 2 horizontal continuous casting lines, and a fully automated ultrasonic testing unit tailored for extrusion billets. The facility also houses two continuous homogenisation plants for billets, along with 6 homogenising chambers and 3 cooling chambers.

The annual production capacity amounts to 165 000 metric tonnes of primary aluminium, 285 000 metric tonnes of cast products and the recycling of 100 000 metric tonnes of scrap aluminium.

The anodes are imported from the Netherlands. The power is supplied by RWE (Trimet, 2023).

Distomon, Greece

Aluminium of Greece operates an industrial complex with an annual production capacity of 860 000 tonnes of alumina and 165 000 tonnes of aluminium. Since 2005, Aluminium of Greece has been a member of Mytilineos Holdings, which also holds ownership of Delphi-Distomon, a mining company, making it a fully vertical aluminium operation in Europe. Anodes are produced in-house. The power is provided by a CHP plant in Viotia (Mytilineos, 2023).

Slatina, Romania

The ALRO is one of the largest vertically integrated aluminium producers. The site includes an Anode plant, Aluminium Smelter, Casting House, Aluminium Eco-Recycling Facility, repairs and spare parts production units, as well as road and rail transportation, among other complementary sections.

ALRO’s production capacity is 265 000 tonnes of primary aluminium and 340 000 tonnes of cast aluminium. The anodes are made in-house. Furthermore, the recycling capacity is around 90 000 tonnes, with plans of expansion to 120 000 tonnes per year. The smelter has its own anode manufacture. The electricity is provided from a coal power plant (Alro, 2023).

Kidričevo, Slovenia

The Talum plant in Kidričevo, Slovenia, has a production capacity of 110 000 tonnes per year. A total of 320 pots are operational across two potlines. The electricity is supplied from various sources; hydro, thermal and nuclear (Talum, 2023).

Žiar nad Hronom, Slovakia

Slovalco is located in Slovakia, with a production capacity 160 000 tonnes of aluminium and alloys annually. However, in 2022, the company faced financial challenges attributed to high energy costs. As a result, Slovalco decided to shift its focus away from primary aluminium production. Instead, the company transitioned to remelting operations, with an expected annual output of approximately 75 000 tonnes.

In January 2023, Slovalco made a significant decision to cease aluminium production in the city after nearly seven decades. This move marked the closure of the remaining 10 cells, effectively bringing an end to the company's primary aluminium production activities. The electricity is supplied by the national grid with a various mix of electricity generation (Hydro, 2023a).

Saint-Jean-de-Maurienne, France

The TRIMET plant is located in the Savoy Alps, with annual production of 145 000 tonnes of primary aluminium and 155 000 tonnes of cast aluminium. The 180 electrolytic cells are divided across two production halls. Additionally, the plant has 11 casting furnaces, three wire rod casting lines, a vertical DC casting unit, an array of cutting, processing, and packaging facilities, another vertical DC casting unit catering to rolling slabs and a small form ingot caster. The site has its own anode production and is powered by hydro power (Trimet, 2023).

Dunkerque, France

A TRIMET-owned facility, Aluminium Dunkerque is a primary aluminium smelting facility located in northern France, in the town of Loon-Plage (Nord). As a major industrial site in the Dunkirk area, it is the largest primary aluminium smelter in Europe. Aluminium Dunkerque alone contributes to approximately two-thirds of France's aluminium production, i.e. it has a capacity of 284 000 tonnes of primary aluminium per year. The smelter has its own anode production plant and is powered by a 360 MW nuclear power plant (Aluminium Dunkerque, 2023).

Sundsvall, Sweden

The Kubal aluminium smelter has a production capacity of 134 000 tonnes per year. There are 242 pots operating in two potlines. The carbon anodes are imported. The power is supplied by a hydro power plant (En+ Group, 2023).

San Ciprian, Spain

The industrial complex of Alcoa San Ciprián, established in 1980 between the municipalities of Cervo and Xove in Lugo, includes two distinct plants: the alumina refinery and the primary aluminium plant.

The primary aluminium plant has a production capacity of 228 000 tonnes per year. With temporary electrolysis cells shut down until January 2024, the aluminium plant continues to operate and supplies customers in Spain and other European countries with ingots for casting, billets for extrusion, and sheets for rolling. The facility has its own anode manufacture. The power to the smelter is supplied by power purchasing agreements (Alcoa, 2023).

Figure 10. Location of EU primary aluminium smelters

Source: JRC based on (European Aluminium, 2023a)

3.1.3 Production of secondary aluminium

Secondary aluminium production involves the recycling of used aluminium products and scrap to create new aluminium alloys and products. Unlike primary aluminium production, which involves the extraction of aluminium from its ore (bauxite), secondary aluminium production focuses on reusing and reprocessing existing aluminium materials. This process is an essential part of sustainable resource management and offers several advantages, including energy savings and reduced environmental impact.

Since its inception in commercial production, aluminium has been actively recycled, with end-of-life recycling contributing to about a fifth of the global aluminium supply today. The decision to recycle aluminium was initially prompted by economic and environmental considerations. Recycling aluminium yields substantial energy savings, utilising a mere 5% of the energy required for primary aluminium production. Across the Western world, recycling rates are impressive, varying from 60% (in the case of EU 75%) for used beverage cans to 85% in the realm of building and construction, and even reaching an impressive 95% in the transportation sector. Remarkably, the quality of aluminium remains unscathed through recycling, enabling repeated recycling cycles and consequently maintaining a high scrap value. Virtually all scrap stemming from aluminium product manufacturing is reintegrated through recycling processes. Although globally the recycling rate[3] is around 35%, the figure varies a lot by region – 60.3% in Europe, 60.1% in South America, 58.4% in North America, 55.9% in Asia (ex. China), 24.7% in China, 8.1% in the Middle East and around 30% in the rest of the world. (International Aluminium, 2023a).

Secondary aluminium scrap sources encompass a variety of materials, contributing to the sustainable recycling of aluminium. These sources include new production off-cuts, used aluminium products, machining swarf, and drosses generated during the melting process. The chemical composition of each type of scrap is crucial in determining its ultimate application within various industries. Aluminium casting alloys, which contain silicon, possess greater flexibility in accommodating a diverse range of scraps due to their broader impurity tolerance compared to wrought alloys. However, it is worth noting that while casting alloys are more permissive in terms of composition, they generally yield lower value-added products than wrought alloys. Consequently, employing specific processes to recycle alloyed aluminium, renders the cost higher which puts an economic constraint for the recycling of certain types of scraps (Wallace, 2011).

For instance, in theory, aluminium-silicon casting alloys could be exclusively produced from extrusion scrap combined with alloying additives like silicon and copper. The diminished value stems from the fact that alloyed scrap is consumed elsewhere in the value chain and remelters have to use more primary aluminium to produce extrusion ingots of desired properties. A significant portion of scrap employed by remelters originates from in-house sources, particularly the remnants generated during the initial billet and slab production processes. To ensure quality and consistency, all collected scrap is meticulously sorted, processed, and categorised into distinct scrap types for potential sale to refiners or remelters. These scraps can find homes both domestically and abroad, conforming to international specifications and trading standards. Notably, the Institute of Scrap Recycling Industries defines approximately 50 distinct grades of aluminium scraps (Institute of Scrap Recycling Industries, 2023), enabling an organised and standardised approach to secondary aluminium production and recycling. This intricate recycling ecosystem contributes to reduced waste, energy savings, and a more environmentally responsible aluminium industry.

The aluminium recycling industry encompasses two main categories: remelters and recyclers, which differ based on the type of scrap they handle. New scrap, also known as process scrap or pre-consumer scrap, consists of surplus materials generated during the production and fabrication of aluminium products before they reach the end consumer. Examples of new scrap include extrusion discards, sheet edge trimmings, turnings, millings, and dross. In contrast, old scrap, referred to as post-consumer scrap, consists of aluminium materials recovered after an aluminium product or component has been manufactured, used, and subsequently collected for recycling. Old scrap may include used aluminium beverage cans, car cylinder heads, window frames, or electrical conductor cable.

Remelters primarily process new scrap to produce aluminium alloy ingots, and this process also occurs to some extent in the cast houses of primary aluminium smelters. On the other hand, refiners process old scrap to manufacture aluminium alloy ingots. It is important to note that the aluminium content of old scrap is often lower than that of new scrap, requiring additional steps to remove impurities.

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[3] Combined recycling of old and new scrap

Remelters typically utilise reverberatory furnaces, while refiners and refiners commonly employ a combination of rotary and reverberatory furnaces. The specific thermal and electricity input for this process is approximately 3.8 GJ per tonne. These figures represent only a small fraction of the energy consumption required for primary aluminium production.

3.1.3.1 New scrap

New scrap offers distinct advantages in secondary aluminium recycling due to their characteristics that facilitate efficient processing and segregation. These scraps can be easily separated into their respective alloy types, aiding in maintaining the quality and consistency of the recycled material. Furthermore, they typically lack attachments or contaminants, reducing the risk of introducing impurities into the recycling process. This quality minimises the need for extensive labour-intensive pre-processing prior to melting.

These scraps often arrive in an uncoated state, which contributes to a higher potential metal yield during the recycling process. Basic pre-processing steps for this category of scrap might include tasks like baling, shearing, and, in more advanced facilities, de-coating procedures for materials coated with lacquer or paint. Additionally, casting trim or rejects can also fall into this category of scrap materials.

To standardise the categorisation of these new production scraps, specifications have been established. These specifications ensure a common understanding between buyers and sellers in the recycling industry. By adhering to these specifications, the recycling industry ensures consistent quality and efficient processing of new production scrap, contributing to the sustainable and environmentally conscious practices of secondary aluminium production.

3.1.3.2 Post-consumer scrap

This scrap category encompasses a wide array of products that have had varying lifespans, ranging from as short as a few weeks for used beverage cans to approximately 12 years for sources like automotive parts. In some cases, such as construction materials, the life span can extend beyond 30 years. These materials are collected from diverse sources and undergo sorting procedures before any further pre-processing can take place for melting. Due to their varied origins, these scraps are prone to contamination by substances such as paint, lacquer coatings, dirt, plastic, oil, grease, as well as a range of metallic and non-metallic attachments.

To prepare this category of scrap for effective recycling, more advanced pre-processing methods are often necessary. These methods go beyond the basic steps of baling and shearing, often requiring more specialised procedures like shredding and advanced separation techniques. Techniques such as magnetic separation, eddy current separation, or heavy media separation may be employed to efficiently segregate the scrap material and remove contaminants. Therefore, recycling old scrap tends to use somewhat more energy due to the listed scrap preparation steps involved (European Aluminium, 2018).

Given the complexity of these scrap sources and the diverse contaminants they may carry, implementing sophisticated pre-processing methods is crucial for ensuring that the recycled material meets quality standards and can be effectively integrated back into the manufacturing process. The utilisation of these advanced techniques demonstrates the commitment of the recycling industry to maximising the value of scrap materials while minimising the environmental impact.

3.1.3.3 Aluminium recycling in EU

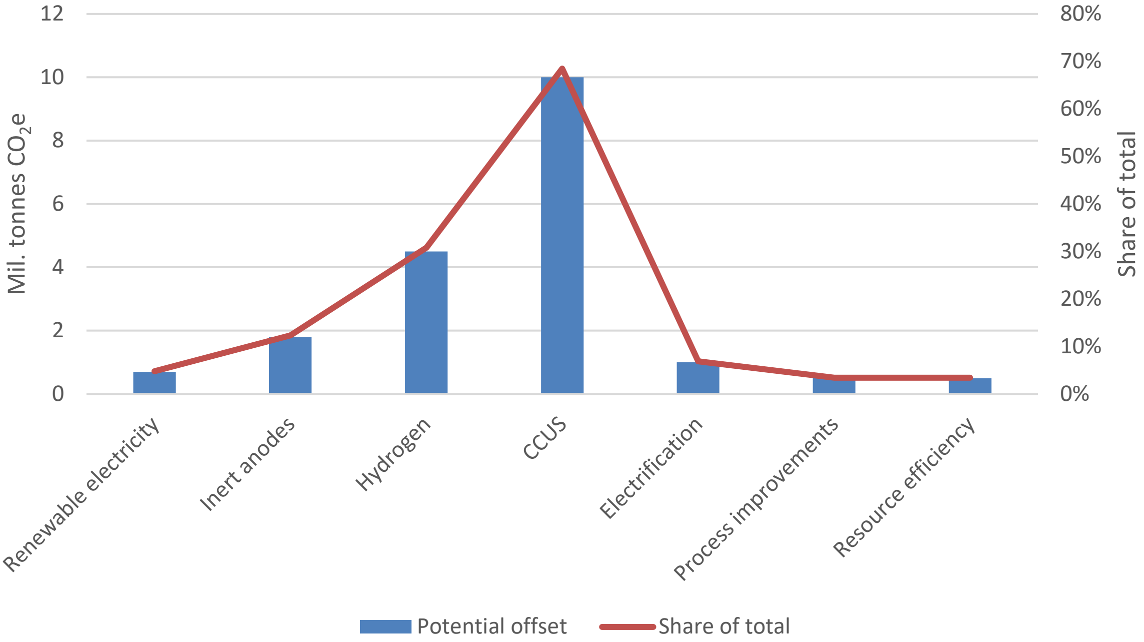
There are over 100 aluminium recycling plants in the EU, with varying capacity and specialty. The recycling quantities are hard to estimate due to the unavailability of data, but a JRC study (Joint Research Centre, 2023) estimates that 5.6 million tonnes of new and old scrap were utilized in the production of aluminium in 2019. The estimation has taken into account the secondary production capacity of each country.

4 Decarbonisation technologies

The decarbonisation potential of the aluminium industry can be divided into three pathways; the decarbonisation of electricity, decarbonisation of direct emissions and resource efficiency (International Aluminium, 2021).

The aluminium industry has the potential to decarbonise. The pathways of decarbonisation are not yet known, since they are dependent on external factors such as market developments, carbon prices and technology development. The analysed technologies are put into EU context and are presented in figure 11. These technologies add up to over 100%. This is due to the fact that the implementation of one technology negates the use of another, e.g. the use of inert anodes in the primary smelter renders the use of CCUS with primary smelters redundant.

Figure 11. Technologies and their decarbonisation potential.



4.1 The decarbonisation of indirect emissions

In the aluminium industry globally, a significant portion (55%) of the sector's total emissions, 616 million tonnes of CO_2e in 2022 (International Aluminium, 2023e), arises from the emissions to produce the electricity consumed during the smelting process (indirect emissions). However, projections under the International Energy Agency's Beyond 2 Degree Scenario (B2DS)[4] (International Energy Agency, 2017) indicate a potential reduction of these emissions to nearly zero by the mid-century. This would be achieved through the gradual phasing out of fossil fuels in favour of cleaner energy sources or by utilising fossil fuels alongside carbon capture, utilisation, and storage (CCUS) technologies. Furthermore, the EU has set clear goals with the European Green Deal of decarbonising its economy and decoupling its growth from resource use. In 2022, the production of primary aluminium in Europe used around 119 TWh of electricity, of which around 2.5% was carbon-based, resulting in the emission of 688 000 tonnes of indirect CO_2 (International Aluminium, 2023d). Achieving the decarbonisation goals would potentially save around 10 million tonnes of CO_2 over the course of 30 years (based on current emissions and the phase-out of carbon-based fuels). If emissions reductions cannot be achieved by using alternative electricity sources, CCUS technology could be employed.

For smelters already integrated into electricity grids, emission reductions will be achieved through the decarbonisation of existing grids or by installing integrated renewable energy into the facility.

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[4] In the B2DS, the energy sector reaches carbon neutrality by 2060 to limit future temperature increases to 1.75°C by 2100, the midpoint of the Paris Agreement's ambition range. This pathway implies that all available policy levers are activated throughout the outlook period in every sector worldwide.

4.2 The decarbonisation of direct emissions

The aluminium sector faces significant challenges in reducing process emissions, which primarily stem from fuel combustion, smelter anode consumption, transportation and the carbon footprints of raw materials. These emissions sources are widespread across the industry, with minor variations in emission intensity, depending on the technology utilized and its performance. Under the International Energy Agency's Beyond 2 Degree Scenario (B2DS)[4] - aligned trajectory, a substantial reduction in these emissions is imperative, aiming to decrease the 650 million tonnes of Business As Usual greenhouse gases emitted from these sources to 250 million tonnes, even as the demand for aluminium is projected to increase by approximately 80% (International Energy Agency, 2017).

About 16% of the sector's emissions in 2022 result from direct fuel combustion for processes such as alumina refining, anode production, casting, remelting, and recycling (International Aluminium, 2023e). Electrification using low-carbon energy sources offers a promising pathway for decarbonising these thermal processes. In cases where electrification is not feasible, alternative options like green hydrogen, concentrated solar thermal energy, and carbon capture utilisation and storage (CCUS) hold potential for emissions reduction.

An additional 10% of emissions emanate directly from the smelting (and refining) process. To tackle these emissions, emerging cell technologies such as inert anodes, which emit oxygen instead of CO_2 during aluminium production, are being explored. While their deployment remains limited, these novel technologies hold promise for significant emissions reduction in the future.

Around 7% of the sector's total emissions come from ancillary materials and transport. These emissions are expected to decrease at a similar rate to direct emissions due to changes in other sectors and the purchasing choices made by aluminium producers.

Specific decarbonisation options include:

- Improved anode technologies: developing advanced anode materials and technologies can improve the efficiency of aluminium production and reduce energy consumption. This could include inert anodes or other innovative approaches.
- Hydrogen as a reducing agent: using hydrogen gas as a reducing agent in the smelting process can replace carbon, leading to "green aluminium" production. However, this approach requires a reliable and sustainable source of hydrogen and further research and development (Braaten, Kjekshus, & Kvande, 2000).
- Carbon capture, utilisation and storage: promising technology for mitigating CO_2 emissions, but needs tailoring for the aluminium industry
- Direct electrification: where feasible using electricity to substitute all processes where fossil fuels are being used. Mainly low and medium temperature processes.
- Other process improvements: specific process tweaks which can be implemented. This are in most cases best practices or best available technologies.

Achieving emission reduction targets will necessitate unprecedented investment efforts. This includes achieving a goal of producing an additional 20 million tonnes of low carbon primary aluminium (a carbon footprint of 4 t CO_2e (Aluminium Stewardship, 2023)), decarbonising the existing 65 million tonnes, and establishing a low-emitting post-consumer scrap recycling industry with a capacity of 60 to 70 million tonnes by 2050 (International Energy Agency, 2017). These efforts underline the sector's commitment to sustainability, even in the face of increasing demand and complex technological challenges.

4.2.1 Inert anodes (TRL 4-5)

The concept of using inert anodes for aluminium electrolysis is not a recent development, with its origins dating back to Charles Martin Hall's patent in 1886. Hall initially experimented with copper anodes but encountered issues as copper quickly dissolved in the electrolyte, rendering the idea impractical. Subsequently, carbon anodes became the industry standard for use in industrial alumina reduction cells.

Inert implies chemical non-reactivity, suggesting that a truly inert anode would neither chemically nor electrochemically react during the electrolysis process. Ideally, it should not be consumed by the anode reaction. Inert anodes have been referred to by various names, including dimensionally stable anodes, non-consumable anodes, and passive anodes.

Alcoa, in 2000, announced its active pursuit of inert anodes, and by 2002, stated that they had proven the scientific feasibility of inert anodes but had yet to address the commercial aspects. This declaration sparked a surge of interest and research in the field, prompting aluminium companies and research institutions to explore potential inert anode materials. Much of this research remains undisclosed due to proprietary concerns.

The inert anode reaction is as follows:

$Al_2O_3 \rightarrow 2\ Al\ (l) + 3/2\ O_2$

As can be seen, the release gas is oxygen instead of carbon dioxide. The development and use of inert anodes presents a few challenges and requirements. Firstly, an ideal inert anode material should have low solubility and reactivity in the electrolyte, making it resistant to dissolution and chemical reactions in the harsh electrolytic environment. It should also withstand exposure to hot oxygen gas produced during the anodic process. Related to that, the anode material must remain physically stable at the operating temperature, ensuring it doesn't degrade, deform, or suffer from thermal shock as well as having high mechanical strength, which is essential to withstand the stresses and strains in the electrolysis cell. Finally, the wear rate should be around 10 mm/year (Gupta & Basu, 2019).

Regarding the challenge and related to chemical and physical stability, the inert anode must have a sufficiently long lifespan while maintaining the purity of the aluminium produced. The corrosion of the anode material can introduce impurities into the aluminium, which is undesirable. The goal is to achieve purity levels consistent with industry standards for smelter-grade aluminium.

As to the benefits, the shift to inert anodes eliminates costs related to consumable carbon anodes, including capital savings, raw material costs, and anode fabrication expenses. This could result in significant operating cost savings, with potential capital cost reductions of 10% to 30% for new potlines (Gupta & Basu, 2019). Inert anodes eliminate the generation of greenhouse gases and emissions from electrolysis cells, all while producing oxygen. This includes the elimination of CO_2, CO, and PFCs, since carbon is no longer used as the anode material. Carbon residues (butts) would also disappear, and fluoride and dust emissions during anode changes would be eliminated. Lastly, inert anodes reduce the need for frequent anode changes, leading to better working conditions and improved occupational health and safety in potrooms.

Presently, two potential types of anodes could be feasible (Krishna Padamata, Singh, Marting Haarberg, & Saevarsdottir, 2023); cermet conducting electrodes and metal anodes. The former are a combination of ceramics and metals and consist of a mixture of oxides and metals, such as $NiFe_2O_4$, NiO, Cu, and Ag, while the latter are metal alloys made out of nickel, iron and copper.

While significant progress has been made in inert anode development, particularly concerning wear and metal purity, operational challenges remain. Companies and research institutions continue to study inert anodes, and rig tests are ongoing. However, the commercial viability of inert anodes has yet to be conclusively proven, and engineering problems must be addressed. The timeline for achieving a proven technology is uncertain, and it may necessitate entirely new cell designs in the future. This makes the deployment of this decarbonisation option more of a mid to long term solution. However, recent developments have reached a significant milestone with the pilot testing of inert anodes in an industrial setting. Reports from Rusal and Elysis claim that the technology is being tested and could be available soon (ELYSIS, 2024) (Rusal, 2024). Although this technology is not yet fully operational, it has been successfully demonstrated at multiple industrial sites, showcasing its potential with an estimated Technology Readiness Level (TRL) of 4-5 (Mission Possible Partnership, 2021).

The current and anticipated costs associated with inert anodes are currently uncertain. The proprietary nature of the technology makes it challenging to gauge the future costs of these anodes when they enter the commercial market or the extent of retrofitting required for existing facilities. In order to be competitive with carbon anodes, it is estimated that inert anodes would need to be priced at approximately EUR 110 to EUR 120 per tonne of aluminium produced (Mission Possible Partnership, 2021).

Currently, there are no known geographical or regional factors that would hinder the use of inert anodes. However, potential challenges could arise from the availability of specific materials required for anode production, such as ceramics. Restrictions in the supply of these materials might present difficulties. Additionally, the capacity for inert anode technology to be truly carbon-free hinges on the regional availability of affordable renewable power, as these processes may require significant energy. The feasibility of achieving a carbon-free operation will be influenced by the accessibility and cost-effectiveness of renewable energy sources in different regions.

Inert anodes have the potential to reduce carbon related direct emissions (Mission Possible Partnership, 2021). In the EU, emissions in 2019 from emissions from anode consumption amounted to 1.8 mil. tCO_2-eq.

4.2.2 Use of hydrogen (TRL 7-9)

Co-feeding hydrogen alongside natural gas for industrial heating is an emerging approach being explored by several industries as part of efforts to reduce carbon emissions and transition to more sustainable energy sources. While this approach is not yet widely tested in aluminium operations, it has potential for reducing the carbon footprint of alumina production (ARENA, 2022).

The TLRs of various types of hydrogen are in principle advanced (TLR 7-9) (International Energy Agency, 2019a), although some sector specific uses, such as the hydrogen calcination are less advanced (TRL 5-6) (ARENA, 2023). The major obstacle is the cost of production – hydrogen produced from fossil fuels, without carbon capture, costs around EUR 1.5/kg; hydrogen produced from fossil fuels with carbon capture costs around EUR 2/kg, while hydrogen produced from renewable energy sources ranges between EUR 3/kg and EUR 5/kg. Low-carbon hydrogen, whether in the form of fossil or RES hydrogen, is currently not as cost-effective as hydrogen produced from fossil fuels without CCUS. However, there are expectations that the costs of both blue and green hydrogen will decrease in the coming decade. Blue hydrogen is expected to remain more affordable than green hydrogen in the short to medium term (Energy Transitions Commission, 2021). This is particularly true in regions where there is access to cheap fossil fuels and cost-effective carbon capture, utilisation, and storage (CCUS) infrastructure. The costs are expected to decrease by 5-10% by 2050. However, it may continue to be a cost-competitive option in areas with limited access to renewable energy and where fossil fuels are inexpensive. The price of green hydrogen is expected to follow the price trend of RES and electrolysers, i.e. decrease its price in the medium to long term. The Hydrogen Council anticipates that by 2030, green hydrogen costs could decline by as much as 30%, reaching a range of EUR 1.40 to EUR 2.30 per kilogram (McKinsey & Company, 2021). In regions with favourable RES conditions, it may even break even with grey hydrogen by 2028, and by 2035 in regions with average conditions.

These projections suggest that green hydrogen will likely become the most affordable option in the long term, thanks to the decreasing costs of renewables and electrolysers. Hydrogen produced from fossil fuels with carbon capture may still have a role in regions with specific constraints, such as limited access to renewable energy and abundant low-cost fossil fuels.

Beyond the cost barrier, the adoption of hydrogen in various industries, including aluminium production, also involves building the necessary infrastructure for its transportation and storage. This infrastructure development requires collaborative efforts between governments and industry at the local, national, and international levels. In the context of industrial heat generation, hydrogen cannot simply replace natural gas as a direct substitute. While certain industries have considered the practice of co-feeding hydrogen alongside other fuels, transitioning to a full replacement of a fuel source would necessitate significant engineering efforts to modify process equipment, ensuring the use of hydrogen without compromising the quality of the end products (International Energy Agency, 2019a).

Hydrogen could theoretically be used as a reducing agent in the aluminium industry.

The proposed reaction of a reducing agent is as follows:

$Al_2O_3\ (s) + 3\ H_2\ (g) \rightarrow 2\ Al\ (l) + 3\ H_2O\ (g)$

This allows for the reduction without the production of any greenhouse gases. Although the idea has been around for almost a hundred years, practical testing shows that many problems occur during the reduction process. A large amount of hydrogen needs to be added to the reaction at a stable rate, while the water produced by the reaction must be constantly removed. High temperatures are required for the reaction, sometimes exceeding the melting point of aluminium (Braaten, Kjekshus, & Kvande, 2000). Tests have been carried out in a laboratory environment and presently no proof of concept technologies exist, making this a long-term decarbonisation option.

4.2.3 Carbon capture, utilisation and storage (7-9)

Carbon capture, utilisation, and storage (CCUS) involves the extraction of direct CO_2 emissions from industrial operations. These emissions can subsequently be transported, utilised as input for creating other products, or permanently stored underground. Historically, CCUS has primarily found applications in the oil and gas sector, particularly for enhanced oil recovery (EOR), which allows companies to leverage the captured carbon. However, current advancements in the CCUS field are concentrated on the reduction and storage of carbon emissions to facilitate the decarbonisation of heavy industries. Within the aluminium sector, CCUS stands out as a potentially practical intermediate solution. This is particularly true for facilities that can readily access cost-effective fossil fuels, lack convenient access to affordable renewable energy sources, are distant from the end of their operational life, and necessary transport and storage infrastructure is available

CO_2 capture technologies from flue gas have been available in the commercial sphere for many years. In the context of primary aluminium production, absorption-based CCUS technology offers the potential for emission capture during both the refining process, relating to the calcination step, targeting emissions from fossil fuel combustion in furnaces, and the smelting process, i.e. CO_2 emissions stemming from carbon anode consumption. This technique involves capturing carbon emissions from flue gas by directing the gas through a solvent that absorbs the CO_2. The technological readiness is TRL 3-4 (Institute for European Studies, 2019).

Transporting CO_2 via pipeline, ship, rail and truck is a well-established practice, but it has yet to be implemented at the scale required to meet future global demands. The industry possesses extensive experience in transporting pressurised gases, so technical feasibility should not pose a hindrance to scaling.

Regarding storage, CO_2 is injected into a porous rock layer deep underground, typically within deep saline formations or depleted oil and gas reservoirs, with an impermeable layer above to prevent leakage. This procedure closely aligns with the established practices in the oil and gas sector. Enhanced oil recovery (EOR) and saline storage are widely adopted within the industry, while storage in depleted reservoirs is currently undergoing pilot testing with TRL 5-9 (International Energy Agency, 2019b).

The barrier for more commercialised deployment is the substantial initial investment required for CCUS. This is unless the captured carbon is integrated into a value chain that generates revenue, such as its utilisation in fertiliser production or enhanced oil recovery (EOR). The expense associated with carbon capture varies significantly, dependent upon the concentration of CO_2 at the emission source and the specific capture technology employed. Costs can range from approximately EUR 15 per tonne of CO_2 for high-concentration emissions to exceeding EUR 100 per tonne for lower-concentration sources (Global CCS Institute, 2021). In the case of flue gas emissions from aluminium smelters, the CO_2 concentration is relatively low, at around 1-1.5% (Lassagne, Gosselin, Désilets, & Iliuta, 2013) as compared to coal power plants where it can reach up to 13.5% (Cheng, et al., 2021), leading to a carbon capture cost well exceeding EUR 100 per tonne of CO_2 (Global CCS Institute, 2021). To reduce this cost, smelters would need to undertake measures such as the redesign of electrolytic pots to eliminate fugitive carbon emissions and the compression of flue gas before capture, which, while technically feasible, comes with a cost. Increasing the concentration of CO_2 to 4% in electrolytic flue gases is enough for efficient carbon capture (Lassagne, Gosselin, Désilets, & Iliuta, 2013). When applied to an alumina refinery, the implementation of carbon capture typically yields a more favourable economic scenario, primarily due to the higher CO_2 concentration in the flue gas. Although there are no direct CO_2 process emissions, the emissions from fossil fuels needed for thermal requirements could be reduced. Nevertheless, the actual cost of CCUS can vary widely depending on the specific refinery and may range from EUR 50 to EUR 80 per tonne of CO_2 (Global CCS Institute, 2021). Given the prices of CO_2 in the EU ETS in October 2023 were around EUR 80 (EEX, 2023), CCUS is a financially viable options for some industries and on the brink of becoming viable for the aluminium industry.

In summary, when developed inert anodes could offer a cost effective, efficient and high CO_2 reduction impact option for the industry. Nevertheless, for smelters situated in proximity to other high-emission industries and capable of leveraging shared transportation and storage infrastructure within industrial clusters, CCUS might remain a viable option. The most significant potential for CCUS lies in its application to refineries, where it can capture emissions stemming from fossil fuel-based industrial heating and steam generation, particularly in regions with readily available and affordable fossil fuels.

4.2.4 Direct electrification

Similar to the electrification initiatives in residential and commercial buildings, industrial electrification primarily entails replacing heat generated through combustion with heat produced from an electrical source. However, unlike the building sectors, the industrial domain encompasses a broader spectrum of required temperatures and potential technologies. Industrial electric technologies can be categorised based on the method they employ to generate heat. Electromagnetic induction technologies, exemplified by induction furnaces in the fabricated metal products and primary metals industries, utilise a changing magnetic field to heat electrically-conductive materials. Dielectric heating technologies, such as microwave and radio frequency heating prevalent in the food and beverage and plastics and rubber industries, leverage high-frequency electromagnetic radiation for heating materials. Resistive heating technologies deliver heat through a heating element or the inherent resistance of the material, as observed in certain types of glass production. Additionally, various electric heating methods include electric arc, infrared radiation, electron beam, and plasma heating. Furthermore, certain industrial electric technologies utilise electricity as an alternative for providing heat indirectly. For instance, electric technologies may harness mechanical work, as seen in mechanical vapour recompression heat pumps, or facilitate material separation using selectively permeable membranes (Wei, McMillan, & de la Rue du Can, 2019).

Electrification in alumina refining involves substituting traditional combustion-based processes with electrical technologies to address the energy needs at various stages of alumina production from bauxite ore. The goal of implementing electrification strategies is to reduce carbon emissions and enhance overall energy efficiency within the alumina refining process. In the initial stages of bauxite processing, which is a crucial step in alumina production, electrification can be applied to tasks like crushing and conveying, where electrically-driven equipment replaces traditional methods. This marks a departure from conventional practices that heavily rely on thermal energy for the Bayer process. The Bayer process includes digestion, where bauxite is mixed with a hot solution of caustic soda to dissolve alumina. Electrification at this stage may involve the use of electric heating elements that utilise electrical energy to provide the necessary heat for digestion. Around 70% of the total fossil fuels used for alumina refining are for steam generation (Australian Aluminium Council Ltd, 2022). Subsequent steps, such as the cooling of sodium aluminate solution to enable precipitation and calcination, can also benefit from electrification. Electrical furnaces for calcination may replace traditional fuel-fired units in this part of the process. Different electric heating methods, such as electromagnetic induction technologies and resistive heating, may be explored for specific stages in alumina refining. Additionally, the implementation of advanced process control and automation systems can optimise energy consumption throughout the refining process. However, challenges include initial capital costs associated with retrofitting or implementing new electric technologies and ensuring a stable and reliable power supply for uninterrupted refining operations .

Electricity has emerged as a viable heat source for aluminium casting as well, displacing conventional gas-fired furnaces. The incorporation of a precise power control unit not enhances energy efficiency but also reduces aluminium waste. There are two main electrification technologies in use: induction coreless furnaces and single-shot induction. Induction coreless furnace are gaining popularity in the casting process due to their efficiency, melting aluminium with a notable efficiency of 67%, surpassing tower melting and holding furnaces (43%) and reverberatory furnaces (37%). The most advanced induction furnaces achieve efficiencies up to 76%, effectively combining melting and holding tasks, eliminating the need for energy-intensive holding stages. Induction furnaces demand 37% less energy per tonne of aluminium cast component compared to tower furnaces. Single-shot Induction utilises rapid induction to swiftly melt limited metal quantities, requiring 50% less energy per tonne of cast component compared to the most efficient gas-fired alternatives. Additionally, it reduces material loss through scaling, presenting a unique application of induction melting in the casting process. As a well-understood process, it doesn't necessitate technological breakthroughs (Beyond Zero Emissions, 2019).

Although alternatives do exist, recent energy market turbulences make the decision to invest difficult. Furthermore, the efficiency gained and the carbon cost reduced may be less than the price of electricity paid for the process. Furthermore, increasing electricity demand could put further demand on the grid. With renewables supplying as much energy as the installed capacity and the weather conditions allow it, fossil fuels could supply the increased demand. This effect, in turn, reduces the net benefit of electrification. Since the goals of decarbonising the EU energy mix have been set, electrification is integral to the decarbonisation of the aluminium industry.

4.2.5 Other process improvements

Waste heat recovery (TRL 7-9)

A significant portion, approximately 30–45%, of the heat generated during aluminium smelting is currently dissipated as waste heat, carried away by exhaust gases. This situation presents an opportunity for the adoption of waste heat recovery systems aimed at lowering overall energy consumption. Various companies offer commercially available technologies for this purpose, including, but not limited to, energy modulation technology, shell heat exchangers, and heat pipes (Yu, 2018). The technology and its efficacy has been demonstrated in scope of the ETEKINA project (ETEKINA, 2021).

Low temperature digestion (TRL 9)

Low-temperature digestion, while technically achievable and currently implemented in selected alumina refineries (such as Hydro's Alunorte alumina refinery (Hydro, 2023b)), is dependent on the quality of the bauxite utilized in the procedure. Bauxite of superior quality permits processing at reduced temperatures, resulting in fewer emissions. This may influence specific sites individually, but its broader industry-wide effect is expected to be limited, given that a substantial alteration in bauxite supply is improbable (Shu-hua, Zong-guo, Ji-ning, & Shi-li, 2009).

Fluidized bed calciners (TRL 9)

Utilising fluidised bed calciners is both technically viable and well-established, with numerous aluminium industry participants already adopting this technology. Compared to rotary calciners (dominantly used in alumina refining), fluidised bed calciners offer greater energy efficiency and the potential for substantial energy and cost reductions, reaching up to 30–35% (Joint Research Centre, 2017).

Electric boilers for low- and mid-heat processes (TRL 4-5)

Shifting from fossil fuel-driven boilers to electric ones, especially heat pump added, is among the more straightforward emission-reduction technologies to adopt. While the concept is theoretically simple, the associated capital expenses can be limiting. As with any electrification initiatives, the availability of affordable renewable energy plays a crucial role (Joint Research Centre, 2017).

Mechanical vapour recompression (TRL 7-8)

Mechanical vapour recompression (MVR) involves the recuperation of waste heat from steam that would otherwise be released during processing. Instead, this steam is collected and channelled into a compressor, where its pressure and temperature are elevated. This process enables the reuse of steam and leads to substantial energy conservation. This could be employed in the refining of alumina, more specifically the digestion of alumina, where the MVR could be powered by renewable energy, to electrify steam production in the alumina refining process thus displacing fossil fuelled boiler steam (RCM Engineering, 2023). Alcoa of Australia Limited has started a pilot project to demonstrate the technology's feasibility (ARENA, 2021)

Carbothermic reduction of alumina (TRL 7-8)

A basic non-electrochemical alternative to the Hall-Héroult process is the carbothermic reduction of alumina, which has been proposed by various researchers in the last 50 years. This process involves the use of carbon (typically in the form of carbon or coke) as a reducing agent to extract aluminium from alumina, instead of the classic electrolysis process. The reaction is as follows:

$Al_2O_3 + 3\ C \rightarrow 2\ Al + 3\ CO$

Carbothermic technology has the potential to produce energy savings of 34 % compared to a modern Hall-Héroult carbon anode technology (Green, 2007).

Lower electrolysis temperature (TRL 7-8)

In the existing process, electrolysis is conducted at high temperatures of 960°C, significantly exceeding the aluminium's melting point, which is at 660°C. In theory, lowering the temperature to near the melting point has the potential to reduce electricity consumption by approximately 1-1.5 MWh per tonne (Luo & Soria Ramirez, 2008). Problems with lowering the temperature and changing the cryolite composition result in lowering alumina solubility, decreasing aluminium solubility, increasing current resistance and increasing vapour pressure. These could be avoided by the introduction of additives. The addition of additives results in having to consider other parameters such as the purity of aluminium, the cell voltage, the handling of the thermally insulating frozen ledge, and the corrosion resistance of lining materials and others (Cassayre, Patrice, Chamelot, & Massot, 2010).

New smelter technologies (TRL 7-9)

The development of new smelter technologies, whose aim is to improve cost-effectiveness results in lowered emission intensity of the final products. An example of such an improvement are the HAL4e Ultra Cells to be deployed in Årdal, Norway (Hydro, 2021). Improvements in Chinese technology which include digital twinning and distributed sensing, steady flow and heat preservation and dusting-free operation for electrolysis increase the overall efficiency, which in turn lowers both operating expenses and emissions (International Aluminium Journal, 2024). With the renewal of potlines which are at the end of their operating life, by employing best available technologies, companies do not only contribute to reducing the carbon footprint, but also to their operating results.

4.3 Resource efficiency

A significant portion of the aluminium produced throughout history remains in use today, amounting to 75% of the more than 1.4 billion tonnes ever produced (International Aluminium, 2020a). This stock of aluminium is readily available for recycling and future reuse. The recycling of post-consumer scrap could play a pivotal role in sustainability efforts, with the potential of globally preventing the need for nearly 20% of primary aluminium and averting approximately 300 million tonnes of CO_2e emissions annually.

Under a Business As Usual (BAU) scenario, post-consumer scrap recycling is projected to increase to 60 million tonnes by 2050. By maximising collection efforts, this figure could further rise to over 70 million tonnes. Certain segments, such as building & construction and automotive, boast high scrap collection rates exceeding 90%. However, the availability of scrap is limited by the long lifetimes of products like cars (International Energy Agency, 2017).

Aluminium used in packaging applications, with shorter lifetimes, witnesses varying recycling rates dependent on factors like local markets, consumer behaviour, and stimulating political landscape. Overall, the global collection rate across all segments stands at over 70%, with some countries achieving near 100% collection rates for specific applications, such as beverage cans in the EU and Brazil (Aluminium for Future Generations, 2023).

The recycling industry has made significant technological improvements, evident by a 70% global increase in the production of recycled aluminium from post-consumer scrap since 2009, coupled with a mere 4% rise in remelting losses (International Aluminium, 2024). Nonetheless, there is room for improvement as around 7 million tonnes of aluminium are currently lost during the recycling process. Without changes in current practices, this figure could escalate to 17 million tonnes annually by 2050. Such losses lead to a replacement of recycled metal with primary aluminium, a less sustainable option due to its higher greenhouse gas emissions.

Adopting near-100% collection rates, enhancing scrap sorting, minimising pre-consumer scrap, and reducing metal losses could potentially lower the need for primary aluminium by 20% globally by 2050 (European Aluminium, 2020). This transformation in aluminium supply requires concerted efforts across the value chain and supportive policy frameworks that foster circularity and incentivise investments in innovative product design and recycling practices. Such comprehensive actions could yield substantial reductions in absolute CO_2e emissions, contributing significantly to overall emissions reduction targets.

The problem currently lies in the prices of aluminium scrap, linked to the price of raw aluminium and the cost of recycling. The cost of recycling in 2019 was around EUR 920-1 160, depending on the type of aluminium scrap (Soo, Peeters, Compston, Doolan, & Duflou, 2019). The price of the aluminium scrap is around EUR 0.35-0.68 per lb of scrap, i.e. EUR 772-1 500 per tonne (Utah Metal Works Inc., 2023), while the price of primary aluminium future is around EUR 2 215 per tonne (with the price fluctuating EUR 1 447-2 485 per tonne in the period before the 2020 turbulences) (Trading Economics, 2023). The Critical Raw Material Act sets a target for the EU of at least 25% recycling rate (European Commission, 2024). This paired with the environmental benefits of secondary aluminium production will aid in secondary production remaining on an increasing trajectory.

In the EU, out of the 13.2 million tonnes consumed in 2019, 4.7 million, or 35% is from recycled aluminium (new and old scrap), two million, or 15% is from primary production, while 50% is imported. In other words, 70% of aluminium ingots produced in EU is from recycled origin (International Aluminium, 2023a) (European Aluminium, 2023a).

5 Drive towards decarbonisation

According to the European Environment Agency (European Environment Agency, 2023b), the total verified emissions[5] of primary aluminium production in 2019 were 4.79 million tonnes of CO_2e, while the total verified emissions of secondary aluminium production were 1.17 million tonnes. In other words, this gives primary aluminium a total emission intensity of 6.8 tonnes of CO_2e/tonne (European Aluminium, 2023a), while secondary remains lower, at 0.25 tonnes of CO_2e/tonne. The global average primary aluminium direct emission intensity is around 13.1 tonnes of CO_2e/tonne. In 2019 (this year is taken before the onset of various disturbances such as the COVID-19 pandemic and the Russo-Ukrainian war), the total consumption in the EU was around 13.2 mil. tonnes of aluminium. Out of those, 50% was from import (6.5 mil. tonnes), 35% from recycling (4.7 mil. tonnes) and 15% (2 mil. tonnes) from primary production. The resulting weighted emission intensity of consumed unwrought aluminium in the EU is around 7.58 tonnes of CO_2e/tonne.

Table 1. Quantities, emission intensities and emissions from aluminium sources in the EU.

	Volume (mil. tonnes)	Emission intensity (tCO_2e/t)	Generated CO_2e (in mil. tonnes)
Primary production	2.0	6.8	13.4
Recycling	4.7	0.25	1.2
Imports	6.5	13.10	85.4
Total	**13.2**	**7.58**	**100**

To satisfy the EU demand of 13.2 mil. tonnes, with a weighted direct emission intensity of 7.58 tCO_2e, a total of around 100 million tonnes of CO_2e had to be emitted. Regarding alumina, the production in 2019 was 6.114 million tonnes, with an emission intensity of 0.400-0.830 tonnes of CO_2 per tonne of alumina (Ecofys, 2009). The total emissions of alumina production amounted to 2.45-5.07 million tonnes of CO_2e.

The average emission from anode consumption per tonne of primary aluminium is around 0.9 tonnes of CO_2 and around 0.5 tonnes of anode is being used per tonne of produced primary aluminium. The best performers achieve an efficiency of around 0.4 tonnes of anode per tonne of primary aluminium (BEUTH, 2019). The total emissions from anode consumptions were around 1.8 million tonnes of CO_2. If an overall efficiency was achieved of only 0.4 tonnes of anode per tonne of aluminium, emissions could potentially be reduced to 1.44 million tonnes – a reduction of 0.36 mil. tonnes per year. If inert anodes were a reality, all carbon consumption-related emissions, of 1.8 million tonnes of CO_2 per year, could be eliminated. This, however, comes at a cost. Current estimates for the capital costs for each cell replacement (i.e. retrofit) range from EUR 1 million to EUR 2 million (United Nations, 2023c). Given that presently around 4 600 cells are operated within the EU, this would amount to a total capital investment of EUR 4.6-9.2 billion. The inert anodes also offer an increase in energy efficiency of up to 25%. Presently, around 688 000 tonnes of CO_2 are emitted through electricity consumption. The implementation of inert anodes would reduce this to 516 000 tonnes. In the best case, this puts the capital investment cost of reducing one tonne of CO_2 at around EUR 1 432. The present TRL for inert anodes is 4-5, giving a very wide estimation of the cost of implementation. With the maturation of the technology, the cost is bound to gown down, giving an incentive to retrofit the cells.

CCUS could potentially eliminate most CO_2 emissions to the atmosphere, but given the operating conditions of aluminium smelting and low CO_2 pressures and concentrations, extensive cell redesign would be required. The CCS Institute puts the cost of carbon capture for the aluminium industry at EUR 180-300 per tonne of CO_2 (Global CCS Institute, 2021), which is considerably higher than the cost in other industries, ranging from EUR 15 to EUR 100. Even the break-even prices of CCUS for the aluminium industry would not suffice, since the

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[5] Every year, operators must submit an emissions report. The data for a given year must be verified by an accredited verifier by 31 March of the following year.

operators would have to reimburse the cost occurred with the retrofit. The other area of use could be in the alumina refining, where the cost is around EUR 50-80 per tonne of CO_2.

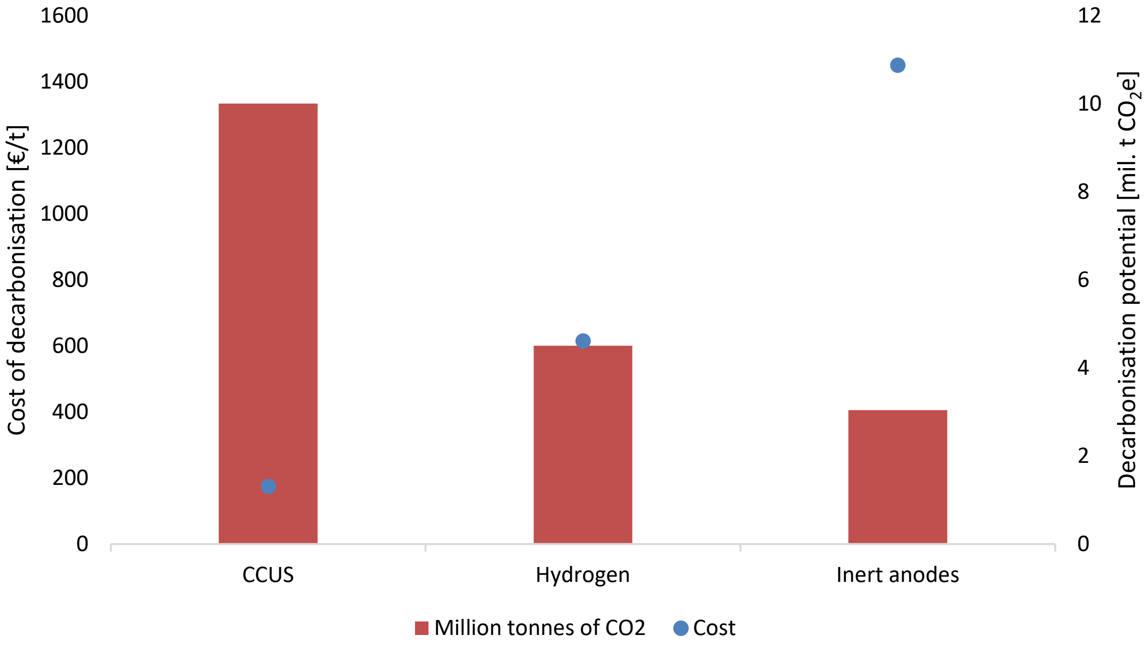
Hydrogen could potentially offset emissions arising from high temperature applications, such as in alumina refining, secondary remelting and anode production. The total thermal energy required from these applications is difficult to estimate, but is around 75 million GJ per year. The amount of required thermal energy to be replaced amounts an equivalent of around 625 million kg of hydrogen. Given that the price of low-carbon hydrogen stands at around EUR 3-5 per kg (Energy Transitions Commission, 2021), a total of EUR 1.8 billion to EUR 3.125 billion would be required to offset the emissions. Assuming the best case, that all the thermal energy provided is from natural gas (55 kg CO_2/GJ), around 4 million tonnes need to be offset. This would put the price of CO_2 reduction via hydrogen at EUR 450-781 per tonne.

Other process improvements are hard to quantify, since both their cost and their deployments are unknown.

The price of technology and the maximum reduced emissions can be seen in the Figure 12. The cost of decarbonisation, expressed in EUR per tonne of CO_2 (blue line) is plotted against the decarbonisation potential of the technology, expressed in millions of tonnes of CO_2 (orange bars). With maturity of a technology, its cost decreases, while the magnitude of decarbonisation potential increases. Looking at the figure it is obvious that presently, the highest decarbonisation at the lowest cost can be achieved by deploying CCUS technologies. Depending on the situation, this may not yet be cost-effective.

Given that around 30% of global emissions are covered by an emission tax in 2023 (up from 7% ten years ago, and from 1% 20 years ago) (IMF, 2022), as the world strives to reach climate stability, the coverage is likely to increase in the coming years. Being a first mover in carbon tax and climate neutrality presents an opportunity to be first to market, and gain a head start on competitiveness and know-how. An increase of global awareness and changes in legislation around the world could in fact reverse the decline of the EU's aluminium industry and make it highly competitive .

Figure 12. Decarbonisation technology cost and reduction quantity.



Source: JRC

Within the EU, emitters of GHGs have to pay for the emissions via the Emission Trading System (EU ETS). The money collected through the ETS is reinvested into the Innovation Fund; one of the largest funds for innovation, low carbon and net-zero technologies. It's aimed to support the EU's climate policy by providing funds for investments into industry and energy. It is a support mechanism for achieving climate neutrality while fostering competitiveness. The money in the fund is gathered through the allowances in the ETS and depends on the carbon price. In 2023, there were 530 mil. allowances. The budget for 2020 until 2030 is projected to be around

EUR 40 bil. The Innovation Fund focuses on highly innovative technologies and flagship projects within Europe that can bring about significant emission reductions (European Commission, 2024). The Innovation Fund presents itself as a unique financing mechanism for producers in the EU. By implementing and adopting innovative technologies in their production process, EU aluminium manufacturers can offset a part of their cost and risk, while keeping the market edge of being first to implement, further establishing their know-how.

6 Conclusions

The European Union’s aluminium sector, although an important and vital part of its economy, European primary productions is slowly declining. The reasons for that are various, but the net-zero goal remains, and all sectors should contribute as far as they can, while remaining competitive.

The literature overview in this report indicates that technology costs reduce as they mature. Other more mature technologies such as CCUS are not as cost-effective in the aluminium as in other industries. This is due to a low CO_2 concentration in the flue gas in aluminium smelters of around 1.5% compared with the concentration in the flue gas of a typical cement facility of 30% or in a coal power plant of 13.5%. Few of the available decarbonisation technologies are cost effective, since the price of their implementation cost currently exceeds the cost of non-reduced CO_2. However, while technologies reduce in price due to maturation and upscaling, CO_2 is likely to increase in price, bringing the tipping point closer.

Some technologies exist, but are yet not universally economically viable, such as CCUS, while others, such as inert anodes, are in their early stages and not yet deployable. Each tonne of imported and domestically produced primary aluminium which is substituted by domestically recycled aluminium reduces CO_2e emissions by 12.85 and 6.55 tonnes, respectively. Direct electrification is another possible pathway, but the fluctuations of electricity prices and high investment costs prevent immediate application. Some activities could be implemented straight away, such as more recycling collection and efficiency, but the cost-effectiveness of this is dependent on market conditions, including the price of scrap, the recycling cost and the price of unwrought aluminium.

Addressing the aluminium decarbonisation challenge requires a multi-faceted approach that combines technological innovation, policy support, and industry collaboration and consumer awareness. Efforts are underway to develop and implement low-carbon and carbon-neutral processes, increase the use of renewable energy sources, advance research into novel materials and technologies, and engage stakeholders to drive sustainability initiatives in aluminium decarbonisation.

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List of Abbreviations and Definitions

AC - Alternating current
BAU - Business as usual
BRDA - Bauxite residue disposal area
CCUS - Carbon capture and utilization
CHP - Combined heat and power
CO2 - Carbon dioxide
CO2e - Carbon dioxide equivalent
DC - Direct current
EFTA - European Free Trade Association
emf - electromotive force
EU - European Union
GJ - Gigajoule
kA - Kiloampere
kWh - Kilowatthour
MJ - Megajoule
MW - Megawatt
MWh - Megawatthour
NFM - Non-ferrous metals
NOx - Ntrious oxide
PBPF - Pre-bake point feed
PFCs - Perfluorocarbons
RER - Recycling efficiency rate
RES - Renewable energy sources
TRL - Technological readiness level
TWh - Terawatthour
UK - United Kingdom

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Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

EU open data

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

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