Technical brief

Aluminium production and CCS/U

A reality check

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About Sandbag

We are a think tank conducting data-driven and **evidence-based advocacy** to improve **EU climate policy**. We combine expertise in **decarbonisation** with **data analysis** to propose policies that drive impactful, cost-effective emissions reductions in the EU and beyond. Through our holistic approach, we make sure our recommendations are not only well-informed and effective but also inclusive, considering economic and geostrategic realities.

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Executive Summary

This technical brief assesses the potential role of carbon capture, storage and utilisation (CCS/U) in the decarbonisation of the European aluminium sector. It finds that **CCS/U is poorly suited to the sector's emissions profile** and could at best offer **very marginal contributions to reducing emission from aluminium production**. More effective, scalable, and economically viable decarbonisation pathways exist and should be prioritised by industry and, where necessary, supported by EU policy.

Aluminium production emissions stem largely from the alumina refining and smelting stages. These processes present distinct challenges. Emissions from **alumina refineries** arise primarily from fossil fuel combustion for heat. These can be largely eliminated in the mid-term through fuel switching, for example by using electric boilers, and energy recovery, through mechanical vapour recompression (MVR). With the right enabling conditions, refinery emissions could reach near zero well before 2050. While CCS/U is technologically viable for refining, it would lock-in fossil fuel use, fail to reduce emissions entirely and is unlikely to be cost-competitive with these alternatives in the long-term. Furthermore, the geographical profile of refineries is not well-aligned with current and emerging CCS infrastructure

In **smelting**, process emissions are generated by the consumption of carbon anodes during electrolysis. CCS/U is challenging as smelter off-gases contain very low concentrations of CO_2 and contaminants, meaning both existing point source or direct air capture (DAC) techniques would need to be tailored specifically for smelters. By contrast, using **inert anodes would eliminate process emissions entirely**. These are under active development by leading firms (Rio Tinto, Alcoa, TRIMET) and could be retrofitted to existing smelters. Though they are yet to reach commercial deployment (currently TRL 4-5), they represent the most promising long-term solution for smelter decarbonisation.

In parallel, the sector must reduce primary aluminium demand through **recycling, circularity, and material efficiency**. Secondary aluminium production requires just 5% of the energy of primary production, yet large volumes of post-consumer scrap are still exported from Europe. Strengthening domestic recycling and scrap retention can accelerate emissions reductions while improving industrial resilience.

In conclusion, **CCS/U is unlikely to be a widely deployed decarbonisation strategy for aluminium producers in Europe**. At most, CCS/U represents a potential option in the medium-term in specific installations in which shared transport and storage infrastructure can be utilised, but even in these cases the merits of CCS/U are questionable in light of the alternatives available, Public and private investment should prioritise electrification of industrial heat in refineries,

Decarbonising aluminium production: A CCS/U reality check

At a global level, carbon capture technologies appear necessary to meet climate objectives, but, crucially, **only in limited and targeted applications**. Carbon Capture and Storage or Utilisation (CCS/U) technologies are unlikely to act as a silver bullet and are not necessarily relevant as a technological solution to decarbonise all industrial processes. It is therefore key to identify what processes are likely to rely on CCS/U, so that resources can be dedicated for scaling up necessary CO_2 transport and storage infrastructure where it is most needed.

Following on from our assessment of CCS/U in the iron and steel sector, we conduct another sectoral deep dive into the relevance of CCS/U, this time focusing on **aluminium production**.

Aluminium: A crucial raw material for Europe's clean transition

Aluminium is a key enabler of the clean transition due to its lightness and strength. It has been recognised as a critical raw material, required by all fifteen key technologies identified across five strategic sectors for the EU economy (Joint Research Centre, 2023b). However, paradoxically it is also **one of the most carbon-intensive industrial metals to produce.**

The **aluminium production process** involves **mining** bauxite, **refining** to produce alumina and **smelting** the alumina to produce aluminium. The aluminium is then **fabricated** and **manufactured** into products. At the end of product life, aluminium can be collected and **recycled** to produce secondary aluminium. So-called 'pre-consumer' scrap is also produced at the fabrication and manufacturing stages which can be collected and used to produce secondary aluminium.

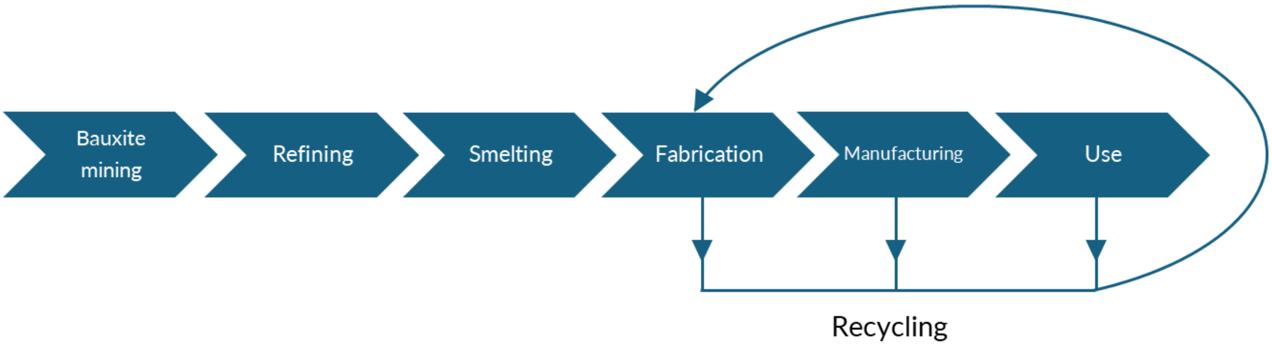

Figure 1. Simplified overview of the aluminium production process

The core primary production steps of **alumina refining,** and **aluminium smelting** (electrolysis) are **responsible for over two thirds of CO_2 emissions from European aluminium production** (Figure 2). The primary cast house and production of the anode also contribute to emissions from primary aluminium production while semi-fabrication (sheet production and extrusion) and recycling (remelting and refining) processes account for the remainder of emissions in Europe.

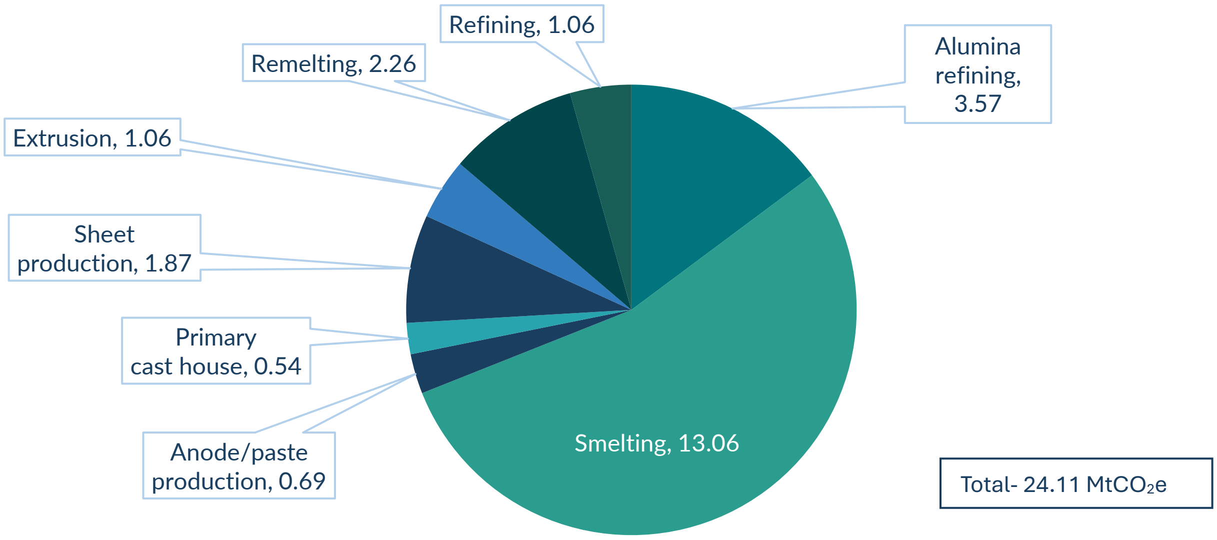

Figure 2. Estimated GHG emissions from European aluminium production ($MtCO_2e$) (European Aluminium, 2023)

Primary aluminium production is declining in Europe, falling by 30% since 2008. This is due to various factors including increased international competition, as well as higher recycling rates. However, the **demand for primary aluminium is likely to remain at least at current levels**, as recycled aluminium cannot cover 100% of the demand for aluminium. Europe is currently the second-largest user of primary aluminium and is expected to remain so until at least 2050 using approximately 9 million tonnes of primary aluminium each year (European Aluminium, 2019).

Therefore, steps need to be taken to reduce emissions from primary aluminium production. Indirect emissions represent a large share (60%) of current primary aluminium production emissions (European Aluminium, 2023). **Decarbonisation of the power sector is therefore expected to drive a major decrease in total CO_2 emissions from primary aluminium smelting** in the short to medium term. However, reduction of direct emissions is also needed for the sector to fully decarbonise.

Capturing emitted CO_2 is one option to tackle direct emissions. However, **the viability of CCS/U will also depend on the availability of alternative decarbonisation methods and when they may become commercially available**. In this technology brief, we will assess the range of options available, focusing on the refining and smelting stages, and evaluate which technologies are likely to enable the most cost-efficient emissions reductions in aluminium production.

Alumina Refineries

In an alumina refinery, **bauxite is transformed into aluminium oxide** (alumina, Al_2O_3), the essential material for primary aluminium production. This is achieved through the Bayer process, which 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.

In total, there are **six alumina refineries in the EU**, located in Ireland, Germany, France, Greece, Romania and Spain, with a combined capacity of over 5 million tonnes per year (Joint Research Centre, 2024a).

CCS/U: Technologically viable but with limited decarbonisation potential in Europe

In alumina refineries there is the **potential to capture emissions stemming from fossil fuel-based industrial heating and steam generation**. European refineries typically use fluidised bed and multi-hearth furnaces which are generally compatible with carbon capture retrofits due to their centralised exhaust streams. However, even within fluidised bed systems, differences in operational design can influence flue gas composition and capture efficiency. As well as other site-specific factors such as bauxite quality, and calcination technology, the flue gas profiles of refineries is heavily dependent on the fuel used. When natural gas is used, as is the case in Europe, gas streams are produced which are relatively clean and low CO_2 concentrations (between 3-10%) compared to the coal-fired plants elsewhere in the world. The presence of trace gases such as carbon monoxide, volatile organic compounds, and alkali metals can also impact the selection and performance of capture solvents or membranes.

The cost of carbon capture can therefore vary greatly depending on the refinery. However, it has been estimated that the cost of capturing carbon at alumina refineries could be as low as 50–80 USD/tCO_2 (Joint Research Centre, 2024a). In a recent assessment of decarbonisation options for the aluminium industry, the JRC concluded that the **most significant potential for CCS/U for aluminium production lies in its application to refineries**, “particularly in regions with readily available and affordable fossil fuels”.

The location of Europe’s alumina refineries must also be considered to assess whether they are likely to be capable of leveraging shared transportation and storage infrastructure. Figure 3 shows the location of the six refineries, along with CO_2 storage sites which are either existing or in development in Europe (Clean Air Task Force, 2025). The wide geographical spread of the refineries is evident, as is the lack of proximity to storage sites; **five of the six refineries are not located within 300 km of CO_2 storage projects existing or currently in development.** Of course, additional geological potential exists in Europe which is still being explored, and efforts to map out and develop a trans-European CO_2 transport network are ongoing (Joint Research Centre, 2024b). However, this infrastrucutre is still some way from development and its eventual reach, availability, and associated connection costs for more remote sites remain highly uncertain. The distance of alumina refineries from existing and emerging storage sites undoubtably limits the potential of CCS for a significant portion of the European alumina refining capacity.

Figure 3. Map of alumina refineries in Europe and CO_2 storage locations in Europe (produced on Google MyMaps, using Clean Air Task Force's Europe Carbon Capture Activity and Project Map (Clean Air Task Force, 2025) and JRC analysis (Joint Research Centre, 2024a))

Emission reductions achievable from point-source capture are also inherently limited. A recent study assessing different options for decarbonisation of alumina production found that CCS and CCU would only achieve 6.88% and 4.33% reductions, respectively (A. Peppas, 2023).[1] This includes capturing emissions from the production of anodes which usually also takes place on the site of alumina refineries. The research shows how relatively small reductions from CCS/U are due to the emissions linked with the operation and energy consumption of the carbon capture system, the geological storage process and, in the case of CCU in this case, the methanol production process.

Dealing with Bauxite Residue: Potential for CCU?

Carbon capture and utilisation (CCU) refers to the use of captured carbon to substitute fossil-based carbon in construction products, chemicals or fuels, for example, hydrogenating captured CO_2 for methanol production. One potential application in the aluminium value chain is the use of captured CO_2 to neutralise bauxite residue (commonly known as 'red mud'), a highly alkaline by-product generated in significant quantities[2] during alumina refining. Current practices for delaing with red mud typically involve long-term containment in large waste deposits. This is energy- and resource-intensive and poses environmental risks, as demonstrated by the 2010 Ajka spill in Hungary (European Parliament, 2015).

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[1] It should be noted that almost 50% of the CO_2 emissions of the production process considered in the study are indirect due to electricity consumption. Decarbonisation of the power sector will almost eradicate these emissions.

[2] For every tonne of alumina produced, approximately 1.5 tonnes of bauxite residue is created (International Aluminium Institute, 2023)

Only a small fraction of global bauxite residue is currently repurposed although some potential reuse pathways are currently being explored. Technical barriers for repurposing this waste include the material's high alkalinity, variable composition, and heavy metal content, all of which complicate processing. Neutralising bauxite residue through reaction with captured CO_2 could simultaneously reduce refining emissions and introduce new avenues for use or disposal. Alcoa was trialling this technology at its Kwinana alumina refinery in Western Australia with the aim to mineralise red mud using CO_2 captured from a nearby ammonia plant, although the refinery announced plans to fully curtail production in 2024 (Alcoa, 2024). Meanwhile, in Europe, the EU-funded ReActiv project is exploring similar CO_2-based valorisation routes for bauxite residue at alumina plants in Greece and Ireland, with a focus on integrating the output into construction materials (ReActiv, 2025)..

Despite the theoretical promise, **the scalability and cost-effectiveness of CCU remains doubtful**. CCU projects at iron and steel production facilities have had limited success. The Steelanol project– ArcelorMittal's flagship CCU project at its steel mill in Ghent- cost EUR 200 million yet only has the potential to utilise 125,000 tonnes of CO_2 per year, just 1.3% of the steel mill's total emissions. Furthermore in this case, emissions are not completely avoided but are rather embedded into the products and released back into the atmosphere throughout the product's lifecycle. CCU can be considered permanent but only if the retention period of the bound carbon is "at least several centuries or longer", according to Commission Delegated Regulation (EU) 2024/2620 (European Commission, 2024).

For alumina refineries, if the CO_2 can be used to neutralise 'red mud' or if neighbouring industrial plants have a demand for CO_2, especially in cases where the CO_2 would end up permanently bound in products, these synergies could be explored. However, even in cases where there is offtake, **CCU is unlikely to be more cost-effective than investing in solutions which would prevent the CO_2 being emitted in the first place at alumina refineries**. Nonetheless, given the scale of the environmental challenge of dealing with bauxite residue, innovative solutions including CO_2 mineralisation should continue to be explored as part of a broader sustainability strategy.

Alternatives: Decarbonising industrial heat

Ultimately, the merit of CCS/U must be considered relative to other decarbonisation technologies, in particular **replacing fossil fuels for the production of industrial heat and steam.** The study by Peppas et al found that replacing natural gas with green hydrogen would lead to a 10.76% reduction in GHG emissions (compared to 6.88% and 4.33% for CCS and CCU respectively) (A. Peppas, 2023). However, producing green hydrogen at the volumes required to provide industrial heat would demand large-scale infrastructure investment and significant policy support. The merits of this must be weighed in comparison with direct electrification of industrial heat, which is also technically viable, more energy efficient and less costly. **Transitioning from fossil fuel-powered to electric boilers is considered "one of the easiest technologies to implement to reduce emissions",** although the capital costs remain high (Mission Possible Partnership, 2021). Furthermore, as with all electrification technologies, access to affordable renewable power remains key.

Another opportunity to reduce emissions is to **recover waste heat from steam** that would otherwise be discharged during processing. With mechanical vapour recompression (MVR), steam is captured and redirected to a compressor that raises the pressure and temperature of the steam, which can then be reused, achieving significant energy savings. While MVR has reached commercial deployment in other sectors (TRL 9) there are still few examples of MVR in operation in the aluminium sector, with the technology only reaching TRL 5 (Mission Possible Partnership, 2021). MVR can be implemented in any location and with a round-trip efficiency of 300%, MVR systems can help reduce the energy demand from fossil fuels by a factor of three (European Aluminium, 2023).

Conclusions: An electrified roadmap for refineries

While there are no technical barriers to implementing CCS/U in alumina refineries, the limited reduction potential, availability of other decarbonisation options and location of many refineries far from potential storage sites means we consider that it is unlikely to play a significant role in reducing emission from alumina refineries in Europe. Notably, **carbon capture at alumina refineries was not included in European Aluminium's roadmap for decarbonising aluminium production** (European Aluminium, 2023). Instead, decarbonisation of alumina production begins with digestion processes moving from fossil fuels to alternative technologies for steam production. Retrofitting alumina refining plants with electric boilers is expected to begin from 2025, together with MVR technology that becomes a viable option closer to 2030. MVR is expected to continue to grow in importance and be deployed for all digestion processes closer to 2045. Electric furnaces are implemented for calcination from 2030 onwards in order to mitigate emissions from fossil fuel power furnaces, and reaches full market penetration by 2040.

Figure 4. Expected deployment of technologies to reduce emissions from alumina refineries (European Aluminium, 2023)

An instructive case study is Hydro's Alunorte refinery in Brazil, which is considered a frontrunner in low emission alumina refining and is aiming for zero GHG emissions by 2040. There is no sign that Hydro foresee a role for carbon capture at this plant. Instead the plant is already **implementing fuel switching and installing electric boilers** (Hydro, 2025).

Aluminium Smelting

The **Hall-Héroult process** is the primary method used for the production of aluminium metal from alumina. This electrochemical process involves the dissolution of alumina in molten salts and reduction through electrolysis to obtain molten aluminium. The majority of emissions (71%) in the aluminium industry globally are from this step, out of which, 78% are from indirect emissions (International Aluminium, 2023). However, European aluminum smelters already use extensive amounts of low-carbon electricity (mainly hydropower, which accounts for 70%), meaning tackling direct emissions from the smelting process now represents the primary challenge in further reducing their emissions (European Aluminium, 2023).

The number of active smelters in the EU has halved in the past 20 years. There are now 10 primary smelters operating in the EU; in Germany (3), France (2) and Greece, Spain, Slovenia, Slovakia and Sweden. The total production capacity of primary aluminium in the EU is around 2.1 million tonnes per year (Joint Research Centre, 2024a).

CCS/U: Low concentration presents challenges

Capturing CO_2 from the Hall-Héroult process is made challenging not only by the low concentration of CO_2 in the flue gas (1-1.5% CO_2 concentration) but also the contamination of off-gas from aluminium smelting with pollutants perfluorocarbons (PFCs), particularly CF_4 and C_2F_6, which form during anode effects. These constraints mean **the use of existing point source capture technologies is not possible for aluminium smelters**. Therefore capture technologies must be adapted for capturing the CO_2 from smelters. Either **point source technologies must be adapted for lower concentrations or direct air capture (DAC) technologies must be adapted for higher concentrations**. In both cases, the current TRL level is low (TRL 3-4) and significant development efforts are required to mature from laboratory to commercial scale (Institute for European Studies, 2019).

The operating conditions of aluminium smelting and low CO_2 pressures and concentrations means **extensive cell redesign would be required** (Joint Research Centre, 2024a). The cost of carbon capture for smelting has therefore been estimated at EUR 180-300 per tonne of CO2, significantly higher than the cost in other industries (EUR 15-100) (Global CCS Institute, 2021). In fact, European Aluminium estimate introducing CCS technology to a smelter would result in a near 50% surge of estimated total CAPEX (European Aluminium, 2023).

Nevertheless, some industry players are forging ahead with developing the technology. Rio Tinto and Hydro have announced they will invest USD 45 million over the next five years to develop carbon capture technologies for aluminium smelting. Hydro have evaluated several capture technologies, and developing a roadmap for testing and piloting of the most promising methods, with the ambition to have an **industrial scale pilot running by 2030**.

The economics of carbon capture become even more challenging at higher capture rates (P. Brandl, 2021). Moreover, due to the low concentration of smelter flue gas, the lines between capturing emissions from industrial point sources (CCS/U) and the atmosphere (carbon dioxide removal, CDR) could become blurred. The question arises **are aluminium producers investing and developing DAC to adapt for use in smelters or to simply offset their ‘residual’ emissions**?

Tellingly Hydro states "*the most likely outcome will be a combination of off-gas capture and direct air capture to eliminate 100% of the emissions*" (Hydro, 2022). It is unlikely that the DAC in question would be used to directly capture emissions from smelters. Studies have shown that even after capturing 99% of the CO_2 from a gas-fired power plant (with a much higher flue gas concentration of 4% CO_2), the resulting CO_2 composition is 400 ppm, which is lower than current atmospheric CO_2 concentrations (approximately 415 ppm) (P. Brandl, 2021). In other words, even when the concentration of CO_2 is high, it is easier to recover the equivalent of that final 1% of emissions from the air, as opposed to trying to capture it directly from the processed flue gas.

It therefore appears as though aluminium producers may look to justify the use of DAC facilities, possibly located away from smelters, to offset their residual emissions. This may be allowed under future EU policy, especially if carbon removals are integrated into the EU ETS. However, the question then arises as to **whether these residual emissions from smelters are really unavoidable.** In other words, does this contradict the principle that carbon removals should only be used for the very hardest to abate emissions? To answer this, **technologies which eliminate the emissions at source must be explored**.

Assessing alternatives: Eliminating direct emissions

As outlined previously, most process emissions arising from smelting result from consumption of carbon anodes. These emissions could be eradicated with the use of inert anodes. Unlike conventional carbon anodes, **inert materials like metal alloys would not degrade and therefore would only produce O_2 rather than CO_2 at the anode, thus rendering the use of CCS/U with primary smelters redundant**. For this reason, inert anodes are sometimes referred to as the "holy grail of the aluminium industry". The use of inert anodes was first suggested by Charles Martin Hall, one of the inventors of the Hall-Héroult process, in 1886. However, the copper anodes initially studied did not work in practice, and carbon anodes have since then been the only practical solution for alumina reduction cells (Kvande, 2011).

As well as eradicating direct CO_2 emissions from the smelting process the use of inert anodes would also have **additional benefits including eliminating SO_2 and PFC emissions**, which would not be captured by CCS/U. Inert anode cells are also expected to be around one-third of the size of a Hall-Héroult cell, while producing the same amount of aluminium, reducing space requirements by 50% (Sai Krishna Padamata, 2023). Additionally, while inert anodes have a higher theoretical energy usage, they allow for a lower anode overvoltage, meaning less energy is actually required.

Substantial progress has been made in inert anode development in recent years, with the technology now reaching pilot stage (TRL 4-5) and **beginning to enter demonstration stage**. Several aluminium producers are currently developing the technology (see box below). In their net zero scenario, European Aluminium project that inert anodes become available by 2035 and **by 2045 smelters will have fully shifted from carbon anodes to inert anodes** (European Aluminium, 2023).

Inert anodes: Promising pilot projects

ELYSIS is a joint venture led by **Rio Tinto** and **Alcoa** aiming to achieve commercialisation of inert anode technology. In June 2024, Rio Tinto announced the installation, by 2027, of 100 kiloamperes (kA) demonstration plant in Quebec, producing up to 2,500 metric tons of aluminium annually. ELYSIS is also planning to license "next-generation electrode technology", with inert anodes lasting more than 30 times longer than traditional carbon-based anodes (ELYSIS, 2024).

Meanwhile **Arctus Aluminium Ltd**, Iceland, in cooperation with **IceTec**, has developed a process using multiple vertical inert metallic anodes and ceramic cathodes in a low-temperature (800°C) electrolyte. The company believes their inert anode design will require 40% less investment costs and 30% less operational cost than a Hall-Héroult cell. Arctus has reached proof of concept by producing high-quality aluminium in laboratory cells and is now scaling up the cells with an industrial partner (**TRIMET**, the largest primary aluminium producer in Germany) for a pilot plant up to 40 kA. The aim is to achieve commercialisation in 2030 (Light Metal Age, 2025).

Of course, in order for inert anodes to reach commercialisation, the cost of this technology must not be prohibitive. The cost of retrofitting inert anodes to existing smelters is particularly crucial. While retrofitting smelters to include inert anodes is possible, substantial upfront costs are needed, in particular to transition from a horizontal to vertical arrangement. However, the expected longer lifetime of inert anodes lead to operating expenditure savings of about 10%, making the technology more financially attractive over the lifetime of a smelter. It has been estimated that the **levelised cost of aluminium production in 2035 will be lower than a carbon anode smelter equipped with CCS** (Mission Possible Partnership, 2022).

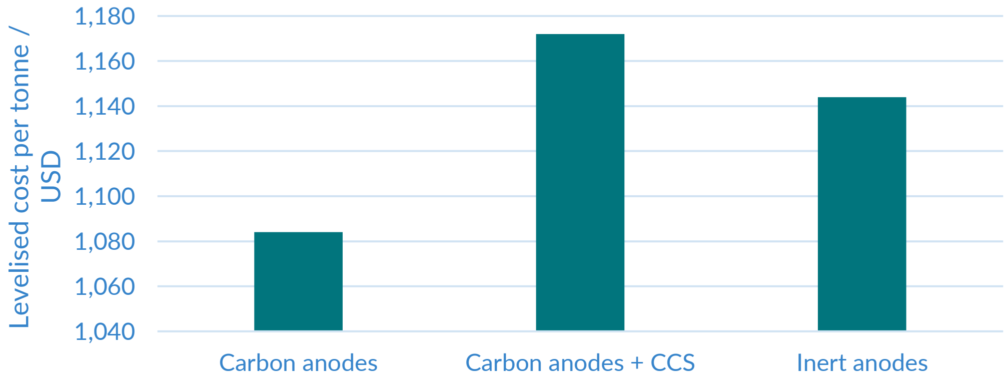

Figure 5. Levelised cost per tonne of aluminium produced using different technologies in Scandinavia in 2035 (Mission Possible Partnership, 2022)

It should be noted that **other electrolysis technologies which eliminate process emissions are also being developed**. Hydro is developing its HalZero technology which involves converting alumina to aluminium chloride prior to electrolysis. In this process, chlorine and carbon are kept in a closed loop, thus O_2 is emitted instead of CO_2 (Hydro, 2025). The ambition is to reach industrial-scale pilot volumes by 2030. While this technology holds promise, one downside is that it is not possible to retrofit this technology to existing smelters.

Conclusions: Stopping emissions at source

The choice of decarbonisation technology will naturally depend on their relative costs and some argue inert anodes could be prohibitively expensive. However, research has shown how a combination of lower electricity intensity, a green premium, and a moderate carbon price would be sufficient to make **investment in inert-anode technology net-present-value (NPV) neutral** (Mission Possible Partnership, 2022). Moreover, we have seen how CCS/U would also be associated with at least a similar cost to inert anodes.

The geographical element is also important to consider. The JRC recently concluded that *"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"* (Joint Research Centre, 2024a). However, as with refineries, European smelters are not typically situated close to storage locations. It is estimated that globally around 35% of smelting production is within the bounds of geological carbon storage formations (Mission Possible Partnership, 2021). A similarly small share of suitably located smelters can be expected in Europe. Aluminium producers may also experience **difficulties gaining access to these storage sites** due to the relatively low direct emissions of aluminium smelters compared to other energy-intensive processes.

The question of timing is also key. Reducing indirect emissions, for example by securing low-carbon power purchase agreements (PPAs), should be a first port-of-call for aluminium producers. By the time CCS/U processes and the surrounding infrastructure is developed, it seems likely that alternative electrolysis technologies will also be nearing commercial viability. In a scenario in which CCS is deployed for smelters, European Aluminium estimated that **the lifetime of CCS facilities would be limited to only about ten years before being phased out and substituted by inert anodes** (European Aluminium, 2023). What's more, the total emissions reductions from CCS over the 2021-2050 period would only be 1.9%. As the authors point out this should be considered against the alternative of directing investments into R&D and implementing technologies, like inert anodes, which are able to support full sector decarbonisation.

Figure 6. Expected deployment of technologies to reduce emissions from aluminium smelters (European Aluminium, 2023)

While CCS/U may have been touted as the most viable mid-term solution for facilities that have access to cheap fossil fuels, have no recourse to affordable renewables, are far from end-of-life and have access to affordable carbon transportation and storage infrastructure (Mission Possible Partnership, 2021), **the number of primary aluminium producers in Europe which fit these criteria is likely to be low**. Overall, technologies that prevent emissions at source seem better placed to enable decarbonisation of aluminium smelters in Europe.

Maximising Recycling: A win-win for Europe

Aluminium is infinitely recyclable without losing its desirable properties. Moreover, the production of secondary aluminium requires **only 5% of the energy required to produce primary aluminium** (Material Economics, 2018). 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 (Joint Research Centre, 2024a). **Efforts must therefore be made to maximise recycling**, with clear benefits not only for the climate but also the competitiveness and self-sufficiency of Europe.

Europe has the highest recycling efficiency rate of any region in the world, meaning it has the highest percentage of waste that is successfully recycled. There are currently over 100 aluminium recycling plants in the EU, recycling 81% of the aluminium scrap potentially available in the region, resulting in the production of 60.3% of the raw aluminium produced in Europe (Joint Research Centre, 2024a). There are two main categories of aluminium recycling: remelters and refiners, which differ based on the type of scrap they handle. Remelters primarily process pre-consumer scrap while refiners process post-consumer scrap to manufacture aluminium alloy ingots. The quantities being recycled are hard to estimate, although JRC estimates that 5.6 million tonnes (total of pre- and post-consumer scrap were used in the production of aluminium in 2019 (Joint Research Centre, 2023a).

However, more still could be done. Currently around 1 million tonnes of aluminium scrap is exported annually. If the industry had access to all the aluminium scrap in the EU, **recycling within Europe could be about 20% higher than current levels** (European Aluminium, 2019). As well as the climate benefits, there would also be advantages in terms of increasing competitiveness and self-sufficiency.

Enhancing competitiveness and self-sufficiency through increased aluminium recycling

The European aluminium industry faces challenges in maintaining competitiveness, as highlighted in the Draghi Report (Draghi, 2024). Key issues highlighted in the report include high energy prices, regulatory burden and an uneven playing field with international competitors, characterised by limited markets for greener products and substantial investment needs for decarbonisation.

Addressing these issues requires a combination of policy support and industry action. The EU's Carbon Border Adjustment Mechanism (CBAM) is a crucial step in preventing carbon leakage, ensuring that European producers are not undercut by competitors from regions with less stringent environmental regulations. At the same time, incentives to improve circularity could strengthen the industry's competitiveness and resilience against external shocks.

A critical vulnerability for the EU aluminium sector is its dependency on imported raw materials. While the EU produces enough alumina to meet demand, it relies heavily on imports for bauxite, with Greece being the only producer in the EU. In 2022 alone, 10.5 million tonnes of bauxite were imported. This dependence exposes the sector to supply chain disruptions and price volatility, making self-sufficiency an urgent priority.

Increasing aluminium recycling offers a solution to these challenges. Higher recycling rates can significantly reduce the EU's reliance on imported bauxite by maximising the use of secondary raw materials. However, the current practice of exporting aluminium scrap to non-EU countries undermines this effort. The shortage of available scrap within Europe not only increases dependency on raw material imports but also raises operational costs for domestic producers, negatively impacting the sector's competitiveness. Measures to retain and process aluminium scrap within Europe, such as stricter export controls or incentives for domestic recycling, are therefore needed.

As global trade tensions and tariffs on imports of aluminium continue to shape the market landscape, **maximising recycling of aluminium within the EU would not just be beneficial for the environment but the economy too**. By maximising recycling rates, the EU can improve the sustainability, competitiveness, and self-sufficiency of its aluminium industry in an increasingly challenging geopolitical and economic climate.

To maximise recycling there is a **need to safeguard scrap availability** within Europe. The Commission also announced its intention to consider '*measures to make recycling of critical raw materials waste within the Union more attractive than their export'* as is stated in the Clean Industrial Deal (European Commission, 2025). Ultimately the cost of producing secondary aluminium (i.e. the cost of scrap, power and recycling) needs to compete with the cost of producing primary aluminium. Ending the provision of free allocation for aluminium production (in conjunction with phasing in of the CBAM) is a key aspect of this as it would make scrap more valuable and increase collection rates.

However, **even with increased recycling efforts, the demand for primary aluminium is likely to persist**. Complete circularity will not be possible due to the foreseen increase in demand for aluminium needed for the clean transition as well as material losses and the long lifetimes of some aluminium products. Hence, solutions are also needed to decarbonise the production of primary aluminium.

A clear path forward for decarbonising aluminium - without CCS/U

We conclude CCS/U is likely to have, at most, a **very limited role in reducing emissions from aluminium production**. This conclusion is primarily drawn from the promise of other technologies which can more cost-effectively reduce GHG emissions from the sector and the fundamental challenges specific to capturing emissions from aluminium production.

- Capturing flue gas from the **smelting** process is not possible with existing commercial point source capture technologies, due to the low concentration of CO_2 and presence of pollutants. When developed, specifically tailored CCS/U may be economically viable for smelters that can exploit shared transport and storage infrastructure, but this is at most envisaged as a solution in the medium-term. In general, inert anodes present a better opportunity to decarbonise direct emissions from smelters in the long term.
- **Refineries** present a better value case than smelters for CCS/U as the flue gas contains a higher concentration of CO_2. Moreover, captured CO_2 could be used to tackle the environmental challenge of bauxite residue. However, alternative solutions (notably electrification, fuel switching and energy recovery) represent a path to deeper, more efficient emissions reductions at refineries.

For CCS, the geographical locations must be considered. While some refineries and smelters are located in the vicinity of storage projects, most notably those close to the North Sea, many are located in southern Europe, often hundreds of kilometres from storage projects currently in development (see Figure 7). This casts further doubt on the viability of CCS at these sites in the short- to medium-term.

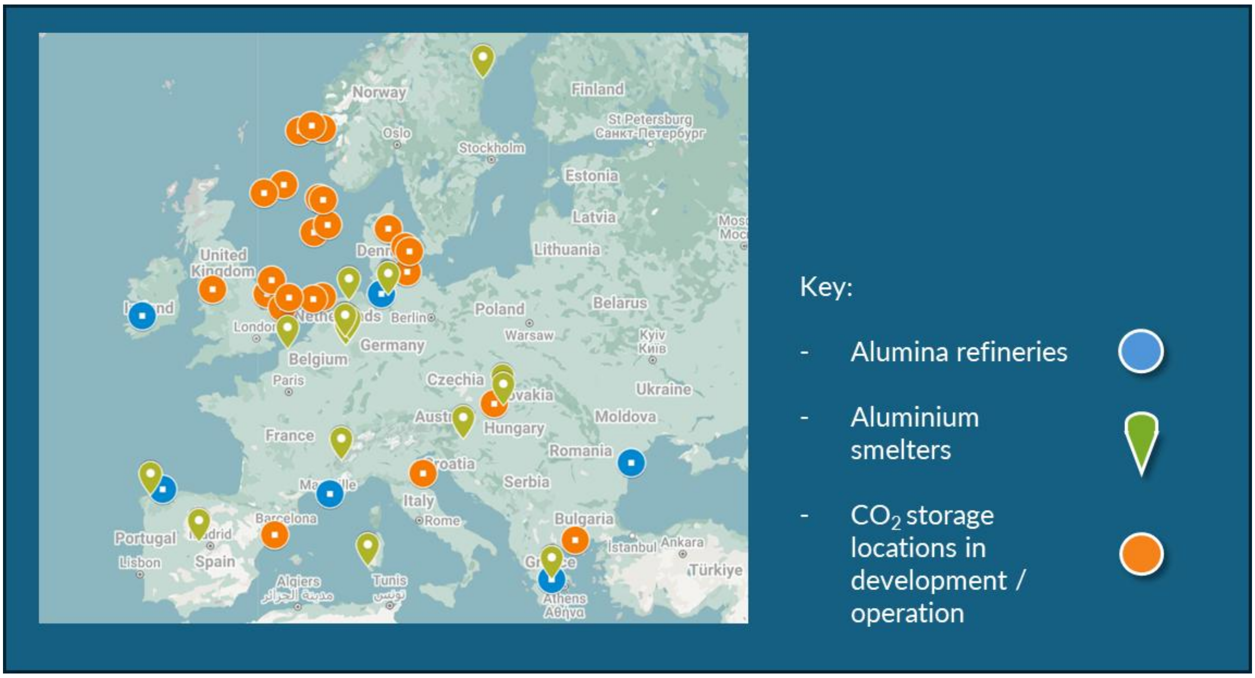

Figure 7. Map of alumina refineries, aluminium smelters and CO_2 storage locations in Europe (produced on Google MyMaps, using data from Sandbag's ETS Dashboard, Clean Air Task Force's Europe Carbon Capture Activity and Project Map)

More general decarbonisation measures must also be pursued. This includes addressing issues of energy supply, material use, and production practices that reduce emissions while supporting the competitiveness and resilience of the European aluminium industry.

While many European smelters already use low carobn (mainly hydropower) electricity, **transitioning to low-carbon electricity** will be key to reducing indirect emissions from refineries and should also be prioritised**.** Not only will securing access to renewable electricity be key but industry may also need to increase its flexibility to adapt to intermittent electricity supply.

Incentivising circularity is also a no-brainer for Europe**.** Maximising recycling rates can improve the sustainability, competitiveness, and self-sufficiency of the EU's aluminium industry in an increasingly challenging geopolitical and economic climate.

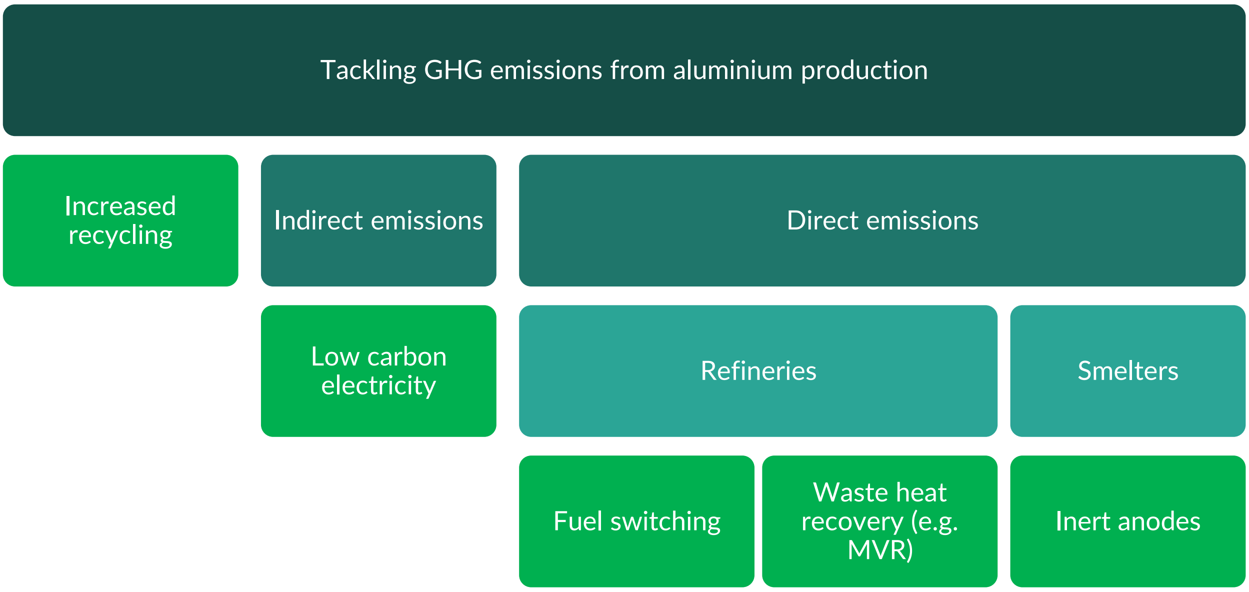

Figure 8. Overview of key decarbonisation technologies for decarbonising aluminium production in Europe

To summarise, we envisage at most **a limited role for CCS/U in aluminium production in Europe**. This vision is seemingly shared by the majority of aluminium producers; in their Net Zero Roadmap, the industry association European Aluminium suggest that capital investments should be used for R&D and implementation of technologies able to support full sector decarbonisation rather than CCS/U (European Aluminium, 2023). In most cases, this would likely also be beneficial from an economic perspective. Recent report shown how, by electrifying and employing technologies like inert anodes which eliminate process emissions, **Europe's aluminium industry can achieve levelised costs lower than many other markets** such as Canada, South America and Russia (Allianz, 2025). A policy framework must now be put in place that can help the sector achieve this transition, encouraging the use of emerging technologies and low-carbon electricity, creating lead markets and increasing circularity in the sector to achieve the deep emissions reductions needed.

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