SCIENCE FOR POLICY BRIEF

# Mapping the transition of the EU aluminium industry to carbon neutrality

2026

## HIGHLIGHTS

- The decarbonisation of electricity supply and use of secondary aluminium are the most cost-effective short-term levers, while inert anodes and electrification emerge as mid- to long-term solutions.
- Net-zero trajectories aim for a 90–95% reduction in emissions by 2050, driven by clean power adoption, breakthrough smelting technologies, and closed-loop recycling systems.
- CCUS shows limited sectoral potential due to high costs and efficiency constraints. Demonstrator projects on electrification and renewable integration aim to substitute fossil-based steam generation with flexible electrified alternatives.
- Without faster deployment of breakthrough technologies, the sector risks missing its emissions reduction targets, undermining both EU climate goals and industrial competitiveness.

## THE CHALLENGE

### Introduction

The aluminium industry is a strategic pillar of the European economy and one of the key energy-intensive industries (EIIs). Aluminium is the world's most used non-ferrous metal, and therefore plays an essential role in enabling the EU's green and digital transitions, with widespread applications in transport, construction, packaging, aerospace, and energy infrastructure. The European aluminium sector covers approximately 6% of global primary aluminium production [1], of which about half comes from the EU and the other half from EFTA countries.

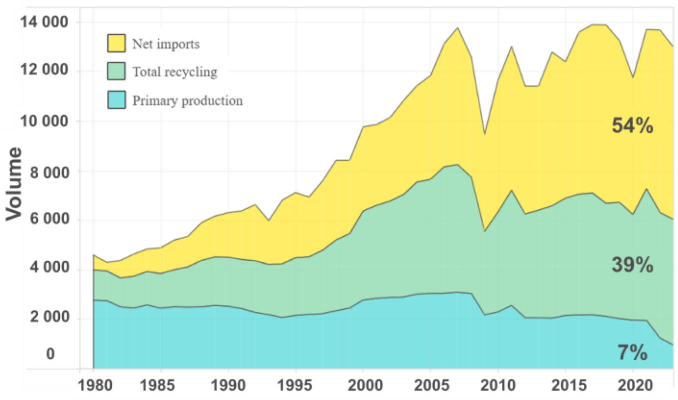
The total primary aluminium production capacity in the EU is approximately 2.1 million tonnes per year. However, over the past two decades, the number of operational smelters has decreased significantly, from 23 in 2002 to 11 in 2022 [2]. As a result, primary aluminium production has also declined from 2.7 million tonnes in 2002 to 1.2 million tonnes in 2022[2], corresponding to 2.75 $Mt_{CO2e}$[1] of direct emissions.

The aluminium industry is responsible for around 2% of global GHG emissions (1.12 $Gt_{CO_2e}$ in 2023 [3]), and only 0.3% of total emissions in the EU. This is due to the fact that secondary (recycled) aluminium accounts for over 60% of European production. On the other hand, European countries rely heavily on imported primary aluminium and precursors like bauxite and alumina, leaving them vulnerable to supply chain disruptions. Globally, demand for aluminium grew by 14.2% between 2019 and 2023, even as emission intensity dropped by 13.6% thanks to less coal use and more recycling [4]. Still, most smelting (up to 61% [5]) runs on fossil fuels, with coal alone powering half the global supply in 2023. As the

[1] Carbon dioxide equivalent is a metric measure used to compare the emissions from various greenhouse gases.

EU pushes for a 55% emissions cut by 2030 and net-zero by 2050, the European aluminium industry must find ways to cut emissions further while staying globally competitive.

**Figure 1 - EU27 aluminium supply by source.**




*Source*: European Aluminium [18]

This factsheet describes the sector's emission sources, the emissions breakdown and the technical paths forward and levers for decarbonisation, with the associated $CO_2$ abatement costs and maturity status. Finally, it evaluates how these developments align with the relevant policy targets and objectives, providing an outlook for the aluminium sector's potential trajectory towards sustainability.

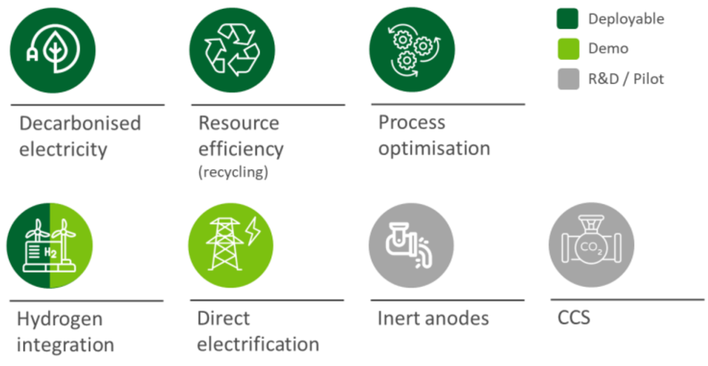
## Production process

Primary aluminium production is an energy-intensive process that begins with bauxite mining and proceeds through several key stages: alumina refining, anode production, electrolysis, and casting. The Bayer process extracts alumina from bauxite ore, which contains about 50% aluminium oxide along with water and impurities. This process involves crushing bauxite, digesting it with caustic soda at high temperatures and pressure, and then filtering out the by-product known as bauxite residue. The resulting alumina crystals are then calcined at 1 200°C to remove water.

The Hall-Héroult process follows. In this step, alumina is dissolved in molten cryolite and subjected to high-temperature electrolysis at around 960 °C. This step consumes roughly 14 790 kWh [6] of electricity per tonne of aluminium and is the main source of $CO_2$ emissions, due to the consumption of carbon anodes that emit $CO_2$ during the process. Globally, about 85% [7] of direct emissions from aluminium production come from alumina refining, anode production, and smelting. While Europe relies mostly on hydropower (93.4% of smelting electricity in 2023) [4], coal still dominates globally, powering 50% of smelters compared to just 0.7% in the EU [4]. After electrolysis, the molten aluminium is refined and cast into various forms such as ingots, slabs and billets.

By contrast, secondary aluminium production uses scrap materials, which are cleaned, melted at lower temperatures (700°C), and refined before casting. Recycling aluminium yields substantial energy savings, utilising only 5% [2] of the energy required for primary aluminium production. This route therefore significantly reduces emissions, making it a key pillar in the transition towards more sustainable production.

**Figure 2 - Stage of development of decarbonisation levers.**

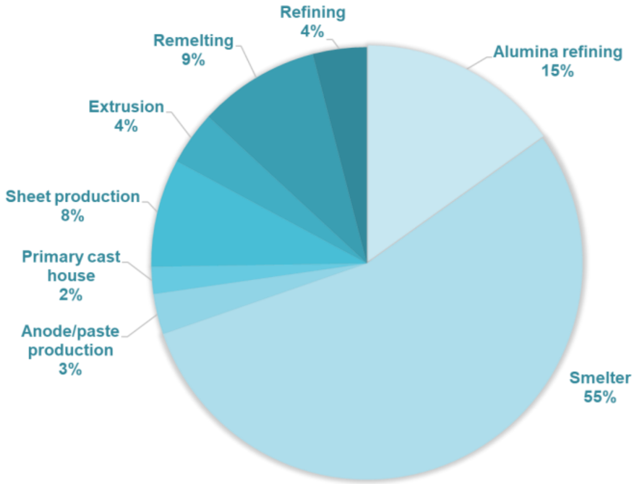



*Source*: JRC

## Current $CO_2$ emissions

In Europe, the aluminium sector emitted approximately 24 $Mt_{CO_2e}$ in 2021 [1], including both direct process and on-site energy emissions, as well as indirect emissions from electricity use. Primary aluminium production was responsible for about 75% of these emissions, followed by recycling (15%) and semi-fabricated products (11%). Most of these emissions originate from the electrolysis stage in primary smelting (Hall-Héroult process), which emits $CO_2$ through the use of carbon anodes and, in addition, releases perfluorocarbons (PFCs, i.e., primarily $CF_4$ and to a lesser extent $C_2F_6$), which are detrimental greenhouse gases. Globally, the industry has made notable progress in reducing its climate impact: PFC emissions per tonne have fallen by nearly 90% [8] since 1990, even as primary aluminium production more than tripled. Moreover, recent data from the International Aluminium Institute shows that for the first time, global aluminium emissions remained stable despite a 3.9% increase in production from 104.1 million tonnes in 2021 to 108.2 million tonnes in 2022 [9]. Over the same period, total greenhouse gas emissions declined slightly from 1.13 to 1.11 $Gt_{CO_2e}$, and the global emissions intensity of primary production fell by 4.4%, from 15.8 to 15.1 $t_{CO_2e}$ per tonne of aluminium [10], demonstrating the sector's gradual but ongoing decarbonisation efforts.

**Figure 3 - Shares of GHG emissions from European aluminium production.**




*Source*: JRC based on data from European Aluminium [1]

### Policy targets and context

The aluminium industry in Europe is subject to a range of EU decarbonisation policies, but it currently lacks binding, sector-specific emission reduction targets. While the European Green Deal and Climate Law set economy-wide goals of reducing greenhouse gas emissions by 55% by 2030 and reaching climate neutrality by 2050, these are implemented through broader instruments like the EU Emissions Trading System (ETS) and the Carbon Border Adjustment Mechanism (CBAM), which impact aluminium producers by pricing emissions and aligning import carbon costs with EU standards. Other policy frameworks such as the Net-Zero Industry Act (NZIA) and REPowerEU may support the sector decarbonisation indirectly, through clean energy and critical materials initiatives. Aluminium is recognised as a critical and strategic raw material under the Critical Raw Materials Act, which means that reducing import dependence and securing green transition supply chains is of paramount importance to secure supply chains for Europe's green and digital transitions. The NZIA also promotes the development of $CO_2$ storage capacity, which is expected to push developments on carbon capture, utilisation and storage (CCUS) projects across the emitting sectors in the EU [11].

## THE WAY FORWARD

### Decarbonisation trajectories[2]

Decarbonisation trajectories for the aluminium industry integrate multiple technologies to achieve steep emissions cuts in line with a shared temporal climate target.

According to **European Aluminium** [12], in order to align with the 1.5°C target, an emissions reduction of at least 37% is necessary by 2030, reaching a 78% decrease by 2040, and 92.4% by 2050 compared to 2021 levels. The result is a decline in emissions from 24.1 $Mt_{CO_2e}$ in 2021 to 1.8 $Mt_{CO_2e}$ in 2050. The steepest reductions are required in primary aluminium production (–93%), with secondary aluminium expected to cut emissions by 88.9%.

The **International Aluminium Institute (IAI)** [13] scenario aims for a 95% global emissions cut by 2050, with a quarter achieved in the coming decade, relying on clean energy, efficiency gains, and expanded recycling. By 2050, primary aluminium output is projected to be 68 Mt (slightly above current levels), with recycling contributing 81 Mt (68 Mt post-consumer, 13 Mt manufacturing scrap). Process emissions from primary aluminium would fall to 0.5 $t_{CO_2e}$/t, below today's recycling intensity (0.6 $t_{CO_2e}$/t).

Insights from the **World Economic Forum (WEF)** [3] emphasise immediate action on low-carbon electricity, recycling, and efficiency, with long-term deployment of electrification, fuel switching, inert anodes, and CCUS; meeting targets would require 223 GW clean power, 9.5 Mt/year hydrogen, and 86 Mt/year CCUS by 2050.

The **International Energy Agency (IEA)** [7] sees aluminium as both critical to the energy transition and a major emitter, requiring emissions intensity cuts of nearly 4% per year to align with its Net Zero by 2050 Scenario, with inert anodes supplying 7% of primary output by 2030 and secondary aluminium exceeding 40% of production.

[2] This factsheet avoids using the term 'pathways' to prevent confusion with the sector-specific decarbonisation pathways published by the European Commission in November 2025. Those sector-specific pathways are intended as a voluntary tool to support companies set their individual decarbonisation targets in line with the European Climate Law. See EC, Making finance flows consistent with climate goals – Climate Action, 2025

**Table 1 - Comparison of different decarbonisation trajectories.**

| Source | 2030 Target | 2050 Target | Key Measures / Technologies | Electricity Needs & Sources | Hydrogen & CCS | Recycling Targets |
|---|---|---|---|---|---|---|
| European Aluminium | −37% vs 2021 (15.2 $Mt_{CO_2e}$) | −92.4% vs 2021 (1.8 $Mt_{CO_2e}$) | Grid decarbonisation, PPAs/self-generation, new digestion tech (2025), electric furnaces (2030), inert anodes (2035) | Low-carbon PPAs & own generation essential; grid alone insufficient | CCS & hydrogen excluded in main trajectories (cost-inefficient) | Secondary aluminium: −88.9% emissions; target over 60% of EU output |
| IAI – 1.5DS | -25% by 2030 | -95% (from 1.1 $Gt_{CO2e}$ to 53 $Mt_{CO2e}$ | Clean energy, efficiency, inert anodes, zero landfill, closed-loop flows | Global clean electricity expansion | CCS not central; focus on process innovation | 81 Mt recycled aluminium (68 Mt post-consumer, 13 Mt manufacturing scrap) |
| WEF | −30% emissions intensity vs 2022 | −97% emissions intensity vs 2022 | Low-carbon electricity, efficiency, inert anodes, CCUS, fuel switching | 223 GW clean power needed by 2050; PPAs growing | 9.5 Mt/year clean $H_2$, 86 Mt/year CCUS by 2050 | Secondary aluminium: contributes to 36% of global production |
| IEA | −18% direct emissions | Near-zero emissions | Inert anodes (7% of primary by 2030), fuel switching, recycling, material efficiency | Near-zero emission electricity | Hydrogen/bioenergy for alumina & recycling; CCS optional | Secondary aluminium: >40% of production by 2030; scrap collection >75% |

*Source*: JRC

In summary, while the four sources vary in detail, they converge on a common strategy: rapid decarbonisation of electricity supply, aggressive expansion of recycling, deployment of breakthrough smelting technologies (notably inert anodes), and selective use of hydrogen or CCUS in hard-to-abate segments.

## Decarbonisation technologies

Decarbonising the aluminium industry requires a portfolio of technologies addressing both indirect and direct emissions.

The decarbonisation of **indirect emissions** focuses on electricity consumption. Electricity use is responsible for more than half of the aluminium industry's global carbon footprint, or around 609 $Mt_{CO2e}$ in 2023 [4]. In Europe, where smelting consumed roughly 116 TWh of electricity that year, most of it already comes from low-carbon sources, with only 2.4% [14] generated from fossil fuels. Decarbonising electricity can be achieved through grid decarbonisation, on-site generation of renewable power, long-term renewable energy purchase agreements, or the use of fossil generation equipped with CCUS. If fully implemented, these measures could all but eliminate indirect emissions by mid-century and save around 10 $Mt_{CO2e}$ over the next 30 years.

**Direct emissions** present a wider challenge. Around 16% come from fuel combustion in refining, anode production, and recycling; 10% are process emissions from smelting; and roughly 7% come from ancillary materials and transport.

Specific decarbonisation options include:

- **Inert anodes** (TRL 4-5) could replace carbon anodes in the Hall–Héroult process with chemically stable materials that emit oxygen instead of $CO_2$. Pilots by Rusal, and Elysis have shown technical feasibility, but barriers remain in terms of cost, durability, and retrofitting. Indeed, current estimates of capital costs for each cell replacement (i.e., retrofit) are in the range of EUR 1-2 million [15]. 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.
- **Hydrogen integration**: Co-feeding hydrogen with natural gas for industrial heating (TRL 7-9) is emerging, though production costs remain the main hurdle. Hydrogen could also serve as a smelting reducing agent ($Al_2O_3 + 3\ H_2 \rightarrow 2\ Al + 3\ H_2O$), theoretically enabling $CO_2$-free aluminium production. However, the concept remains at lab scale with significant technical challenges. Given that the price of low-carbon hydrogen stands at EUR 3-5 per kg [16], a total of EUR 1.8-3.1 billion would be required to offset the emissions. Assuming the best case, that all the thermal energy provided is from natural gas (55 $kg_{CO2}$/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.
- **CCUS**: In the context of primary aluminium production, CCUS technologies offer the potential for capturing emissions generated during the refining process, (due to the calcination step), and from fossil fuel combustion in furnaces and the smelting process. In the case of flue gas emissions from aluminium smelters, the $CO_2$ concentration is relatively low, at around 1-1.5% [17], leading to a carbon capture cost of EUR 180–300 per tonne of $CO_2$.

- **Direct electrification**: Substituting electricity for fossil fuels in low- and medium-temperature processes, where feasible. This is seen as a key solution by the industry.
- **Process optimisation**: Implementing best practices and best available technologies to improve efficiency and reduce fuel use.

Another pillar, **resource efficiency**, offers immediate, largescale benefits. Aluminium is infinitely recyclable, and around three-quarters of all metal ever produced is still in use. Recycling post-consumer scrap uses up to 95% less energy than primary production and could avoid 20% of primary demand globally by 2050. In EU production, recycled aluminium is dominant, but better scrap collection, sorting, and loss prevention are essential to unlock further gains. However, progress is limited by the availability of scrap, which depends on the turnover of long-lived aluminium products, and is further reduced by growing exports that drain domestic recycling feedstock. In response, the EU is introducing measures to secure strategic scrap streams and strengthen the circular aluminium value chain [18].

**Figure 4 - Decarbonisation levers $CO_2$ abatement potential and cost.**

| Lever | TRL | $CO_2$ abatement potential | $CO_2$ abatement cost [EUR/$t_{CO2}$] |
|---|---|---|---|
| Decarbonised electricity | 9 | up to 50% | - |
| Resource efficiency (recycling) | 9 | 95% | - |
| Process optimisation | 7 - 9 | 30-45% | - |
| Hydrogen integration | 5 - 9 | 30% | 450 - 781 |
| Direct electrification | 7 - 9 | 5-10% | - |
| Inert anodes | 4 - 5 | 10% | - |
| CCS | 4 - 5 | up to 70% | 180 - 300 |

*Source*: JRC

## STATE OF DEVELOPMENT

### Industrial pledges

Major primary aluminium producers in Europe have each laid out decarbonisation strategies with varying timelines and technologies. Norsk Hydro aims for net-zero emissions by 2050, with a 30% reduction by 2030, pursuing innovations such as its *HalZero* zero-carbon electrolysis process, carbon capture retrofits, largescale recycling of post-consumer scrap, and the electrification of alumina refining. The company focuses on emissions across the value chain to bring the carbon footprint of aluminium production down to net-zero. TRIMET has set a target of climate-neutral production by 2045, focusing on the development of inert anode technology, hydrogen-based processes, and extensive measures in scrap recycling and waste-heat recovery. AMAG plans to achieve $CO_2$-neutral operations by 2050, following a three-pillar roadmap of maximising recycling, improving energy efficiency, and substituting fossil fuels with renewables and future hydrogen, underpinned by long-term wind and hydro PPAs and the expansion of rooftop solar. Alongside decarbonisation, AMAG has also invested in environmental stewardship, including water efficiency, forest and green-space management, and even partnerships for beekeeping around its Ranshofen site. Constellium is targeting a 30% reduction in greenhouse gas intensity and 50% recycled aluminium input by 2030 (vs 2021 levels). Its initiatives include the development of the first industrial-scale aluminium slab production using hydrogen combustion, successfully demonstrated at C-TEC, Constellium's primary R&D centre, which will be further processed at their Neuf-Brisach site. Although no specific target for net-zero has been announced by ALRO, the group is investing in photovoltaic power, improved fume treatment, and modernisation of its cast house to lower emissions.

### Demonstrators

Several EU-funded demonstrator projects are targeting the decarbonisation of the aluminium sector through complementary technological, digital and symbiotic approaches. Projects on electrification and renewable integration are demonstrating how fossil-based steam generation can be directly substituted with flexible electrified alternatives: AAL SEB is installing a 25 MW high-pressure electric boiler at Aughinish Alumina's aluminium refinery in Ireland; H2GLASS, on the other hand, aims to pioneer 100% hydrogen combustion coupled with smart control systems (currently TRL 5); and HyInHeat aims to integrate hydrogen as a fuel for high-temperature heating processes in energy-intensive industries, particularly in the aluminium and steel sectors. Shifting the focus to resource efficiency and industrial symbiosis can tackle the challenge of by-products and residues: ENSUREAL explored a zero-waste alumina process by combining the Bayer and Pedersen routes, while ReActiv is transforming bauxite residue into supplementary cementitious materials. Other projects focus on digitalisation: for instance, TRINEFLEX is developing end-to-end digital toolkits, including digital twins and decision-support systems, to optimise energy use, integrate clean energy and enable systemic change across energy-intensive industries.

### Evaluation of progress and alignment with policy and industry targets

Europe's aluminium industry is relatively well aligned with EU decarbonisation objectives, largely due to its reliance on low-carbon electricity, with over 97% of smelting already powered by renewable or nuclear sources. However, the IEA [7] considers the global aluminium sector not to be on track, due to the need to accelerate its emissions decline. In order to get on track, it needs to develop and deploy near-zero emission technologies to achieve deep emissions reductions from alumina refining and both primary and recycled aluminium production, while the industry and its customers need to increase scrap collection, sorting and recycling. Moreover, direct process emissions remain a more complex challenge, as primary aluminium production is highly energy-intensive and low-emission technologies such as inert anodes, hydrogen combustion, electrification and CCUS are still at early demonstration stages, facing high costs and infrastructure gaps. Without accelerated deployment and stronger policy support, the industry risks falling short of its voluntary 37% emission reduction target by 2030, undermining EU climate goals. Key priorities include securing competitively priced clean electricity through PPAs and grid upgrades, supporting pilot-to-commercial scaling of breakthrough technologies via instruments like the Innovation Fund, and coordinating hydrogen and $CO_2$ infrastructure under the Net-Zero Industry Act. At the same time, policy frameworks such as the ETS and CBAM provide strong incentives by raising the cost of carbon-intensive production and preventing carbon leakage, while the Circular Economy Action Plan and Raw Materials Strategy highlight recycling as an immediate lever.

## CONCLUSIONS

The decarbonisation of the aluminium sector shows clear progress but also structural challenges. Europe leads globally in reducing indirect emissions, with over 97% of smelting already powered by renewable or nuclear electricity, yet direct process emissions remain difficult to abate. Breakthrough options such as inert anodes, hydrogen combustion, and CCUS are strategically aligned with EU climate priorities, but their commercialisation is still at an early stage and faces cost and scalability barriers. Recycling provides an immediate way forward, though improvements in collection, sorting, and traceability are needed to maximise this advantage. To accelerate progress, policy should expand access to low-cost renewable electricity, support demonstrator technologies and ensure coordinated planning for hydrogen and $CO_2$ infrastructure. Without faster deployment of breakthrough technologies, however, the sector risks missing its emissions reduction targets, undermining both EU climate goals and industrial competitiveness. Closer collaboration between policymakers and industry will be essential to scale innovation, strengthen recycling systems, and establish aluminium as a pillar of Europe's climate-neutral and resource-secure economy.

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