CHENAVARI

WHITE PAPER

Industry in Transformation: Decarbonising Aluminium

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1 Introduction

Aluminium production exceeds 65 million tonnes annually (International Aluminium, 2022), underpinning industries such as transportation, construction, packaging, defence, and electronics. While its recyclability aligns well with circular economy principles, primary production remains highly energy-intensive, often described as "solid electricity" (Bloomberg, 2021).

In addition, it is also highly emissions-intensive due to the use of traditional methods, like the Hall-Héroult smelting process, which are heavily reliant on carbon-based anodes and fossil fuels, leading to substantial CO2 emissions.

Primary aluminium production has a global carbon intensity exceeding 14 tCO_2 per tonne of aluminium produced (European Aluminium, 2025) – significantly higher than other major industrial sectors. To achieve net-zero emissions, both energy-related and process-related sources of emissions need transformative change.

This is particularly important as aluminium is a key metal in the EU's energy transition, with an additional 10 Mt needed to support the target of 600 GW of solar PV capacity by 2030 (Federation of Aluminium Consumers in Europe, 2024).

This whitepaper delves into the emissions profile of the aluminium industry, highlights areas ripe for innovation, and outlines strategies for sustainable production practices.

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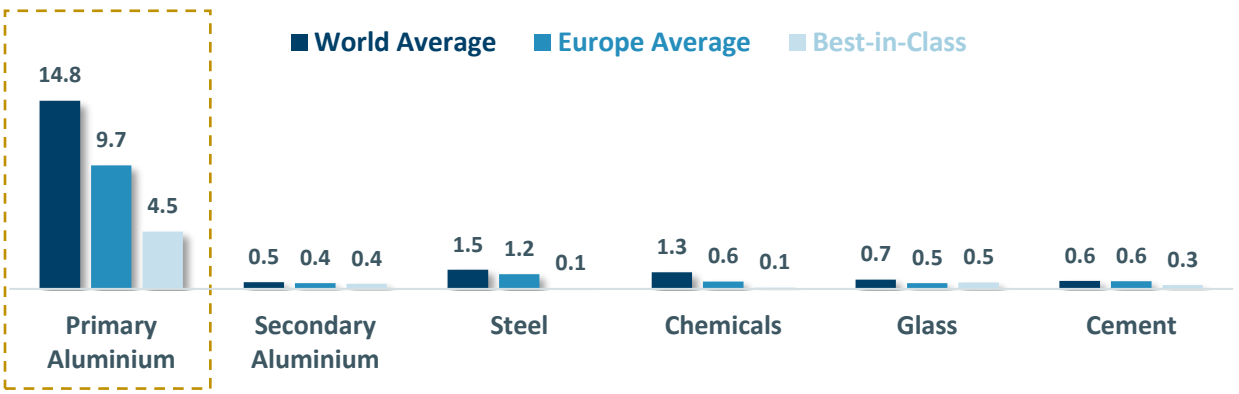
Figure 1: Carbon Intensity of Key Industrial Sectors
(tonne of CO2 equivalent per tonne of material produced)



Notes: All figures are reported in tonnes of CO2 equivalent per tonne of material produced. Figures provided are approximates only and may vary based on measurement dates, scope, and methodology. **Primary Aluminium:** WA = European Aluminium, 2025. EA = European Aluminium, 2024. BA = Carbometrix, 2024. **Secondary Aluminium:** WA = International Aluminium, 2022. EA = International Aluminium, 2018. BA = Norsk Hydro, 2025. **Steel:** WA = Net Zero Industry Tracker, 2024. EA = European Commission JRC Technical Report, 2022. BA = SSAB, 2024. **Chemicals:** WA = Net Zero Industry Tracker, 2024. EA = European Environment Agency, 2020; European Environment Agency, 2023. BA = BASF, 2023; Eurostat, 2024. **Glass:** WA = European Commission, 2022; Gradeall International, 2024. EA = Zier et al, 2021. BA = Pilkington, 2024. **Cement:** WA = Net Zero Industry Tracker, 2024. EA = European Union, 2021. BA = Heidelberg, 2024.

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2 How Much Carbon Does Aluminium Generate

Four Primary Stages of Aluminium Value Chain

Emissions Source

(International Aluminium Institute, 2023)

Bauxite Mining
CO_2 Intensity: <0.1 tCO_2/t

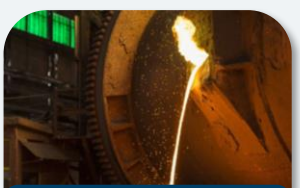
Extraction of bauxite ore, predominantly from tropical regions, involves heavy machinery and transportation. Sustainable practices, such as land rehabilitation, can mitigate environmental damage (World Aluminium, 2022).

Thermal Energy	71%
Electricity	29%

Refining
CO_2 Intensity: 2.4 tCO_2/t

The Bayer process converts bauxite into alumina using sodium hydroxide and high temperatures, creating emissions and by-products like red mud that require proper management (International Aluminium Institute, 2021).

Thermal Energy	63%
Ancillary Raw Materials	17%
Transport	13%
Electricity	8%



Smelting
CO_2 Intensity: 12.2* tCO_2/t

**includes anode production*

Using the Hall-Héroult process, alumina is reduced to aluminium through electrolysis in molten cryolite. This stage consumes significant energy and accounts for nearly 70% of emissions across the value chain (International Aluminium Institute, 2023).

Electricity	71%
Process CO_2	13%
Ancillary Raw Materials	7%
Other GHGs	7%
Thermal Energy	2%
Transport	1%

Casting
CO_2 Intensity: 0.1 tCO_2/t

Molten aluminium is shaped into products such as ingots and billets. Recycling plays a vital role here, as remelting scrap requires a fraction of the energy compared to primary production (European Commission, 2021).

Thermal Energy	56%
Electricity	44%

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3 Why Aluminium is Hard to Decarbonise

Energy Intensity

Aluminium production requires consistent, high-intensity energy to power smelters during electrolysis and sustain elevated temperatures in alumina refining.

Process Emissions

The smelting process generates unavoidable emissions as carbon anodes facilitate the chemical reactions necessary for metal reduction.

Energy intensity and process emissions are the two main reasons why the aluminium sector is often labelled as hard-to-abate. Additionally, several structural factors further compound the decarbonisation challenge, as outlined below:

COST COMPETITIVENESS

Aluminium demand is projected to grow 80% by 2050 (Mission Possible Partnership, 2022). Its unique properties make it essential for sectors where few substitutes exist. However, transitioning to low-carbon aluminium to meet this demand comes with higher costs, requiring strong incentives for both primary producers and end users.

FUNDING REQUIREMENTS

Approximately USD 1 trillion is needed to decarbonise the primary aluminium sector by 2050 (Mission Possible Partnership, 2022), requiring substantial investment in low-carbon electricity generation, advanced smelting and refining technologies, secondary aluminium, and other key areas.

TECHNOLOGICAL READINESS

Decarbonisation paths vary by readiness and scalability, with electricity decarbonisation being the most advanced and commercially available. In contrast, critical technologies for process emissions are still under development and would require further investment before wide-scale deployment.

POLICY SUPPORT

Policy is key to the net-zero transition, particularly in creating a level playing field, promoting secondary production, and driving sector-specific decarbonisation solutions. A well-designed mix of policy instruments and incentives is essential to maximise impact and achieve broader sustainability goals.

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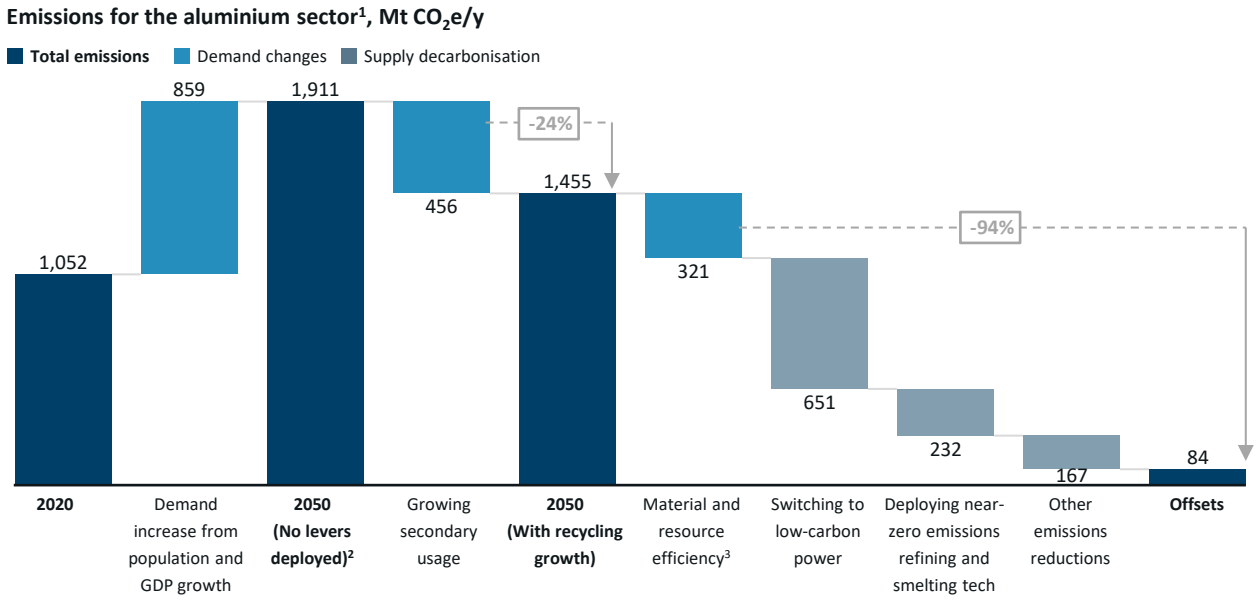
4 Decarbonisation Strategies

Figure 2: Overview of Emissions Reduction Potential by Decarbonisation Lever



[1] Includes all direct and indirect emissions along the value chain for primary and secondary aluminium production (i.e., mining, alumina refining, aluminium smelting, anode production, casting, fabrication, recycling and transport). [2] IAI's Reference scenario, except for primary/secondary production ratio, which is assumed constant between 2020 and 2050; 2020 carbon intensity of aluminium assumed constant. [3] Based on demand projections from IAI's 1.5°C scenario.

Source: Adapted from Mission Possible Partnership (Making Net Zero Aluminium Possible).

Reducing emissions from aluminium production involves a multi-faceted approach across the value chain. Key strategies include integrating low-carbon energy, enhancing recycling practices, improving resource efficiency, and adopting innovative technologies.

As highlighted in Figure 2, switching to low-carbon power offers the greatest emissions reduction potential in the sector. The use of low-carbon power grids, combined with power purchase agreements (PPAs) from renewable energy producers, is the most technologically advanced and commercially available solution.

Secondary production, with a carbon intensity of just 0.5 tCO_2 per tonne of aluminium produced (Figure 1), also holds significant potential, as it shares the same level of technological readiness and market availability. However, significant barriers remain and must be addressed to unlock its full potential.

In the medium- to long-term, near-zero emission refining and smelting technologies will be essential, though their adoption depends on the availability of low-carbon power and broader market deployment.

On the demand side, improving material efficiency requires close collaboration among producers to maximise product circularity. However, achieving this goal is complex, as it also depends on changes in end-user behaviour – factors made more challenging by aluminium's widespread use across multiple sectors (Mission Possible Partnership, 2022).

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Low-Carbon Energy Integration

Transitioning to low-carbon energy sources like solar, wind, hydropower, and nuclear offers one of the most impactful decarbonisation pathways. The aluminium industry currently consumes around 1,000 TWh of electricity annually, representing about 4% of global electricity demand. Of this 25-30% is already supplied low-carbon sources, such as hydropower (World Economic Forum, 2023).

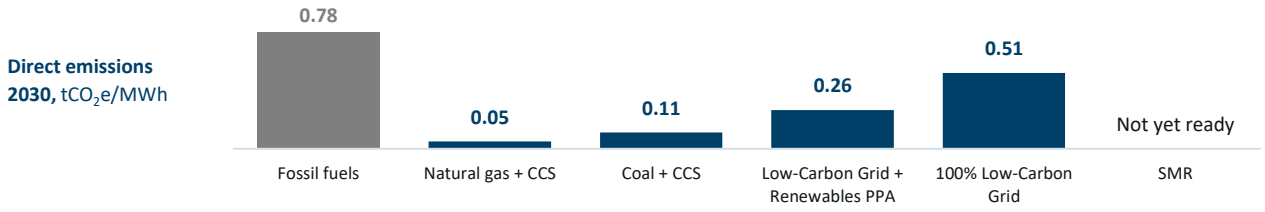
To fully decarbonise, the industry must scale up electricity use to approximately 1,000 TWh annually by 2050. Overcoming challenges like intermittency will require complementary technologies such as battery storage and green hydrogen (BloombergNEF, 2021).

The Hall-Héroult process, used in the smelting process of primary aluminium production, is highly energy-intensive and has a carbon intensity 12.2 tCO_2 per tonne of aluminium produced. In Europe, for instance, although smelters mainly rely on hydropower, local energy grids, and PPAs for their power mix, these solutions alone are insufficient to meet net zero targets.

Achieving this goal requires the development of integrated solutions, including the development of carbon capture and storage (CCS) technologies for fossil-fuel based plants, switching to a decarbonised grid with a reliable mix of low-carbon energy sources – such as hydropower and nuclear for baseload power – securing renewable energy through PPAs, and exploring baseload capable nuclear small modulator reactors (SMRs) in the future.

In addition, while transitioning to low-carbon power is the most readily available solution with the highest Technological Readiness Level (Figure 3), constant availability of low-carbon power, the pace of grid decarbonisation, and cost efficiency will remain crucial factors for producers in their efforts to reduce direct emissions (Mission Possible Partnership, 2022).

Figure 3: Comparison of Conventional and Low-Carbon Smelter Power Supply Technologies



	Fossil fuels	Natural gas + CCS	Coal + CCS	Low-Carbon Grid + Renewables PPA	100% Low-Carbon Grid	SMR
Commercial Readiness Year	-	2027	2020	2020	2020	2035
Technological Readiness Level	9	8	9	9	9	4-5

Source: Adapted from Mission Possible Partnership (Making Net Zero Aluminium Possible).

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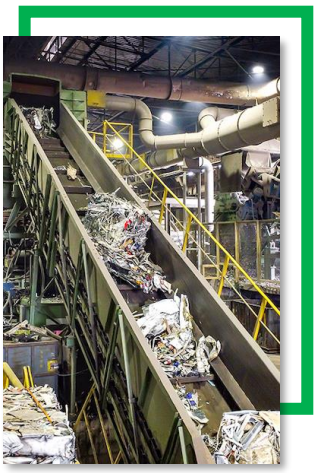
Recycling and Circular Economy

Recycling aluminium is a highly efficient way to reduce emissions, as it requires only 5% of the energy needed for primary production. Expanding recycling rates, improving scrap sorting, and promoting closed-loop systems can substantially reduce the sector's carbon footprint. Key initiatives include:

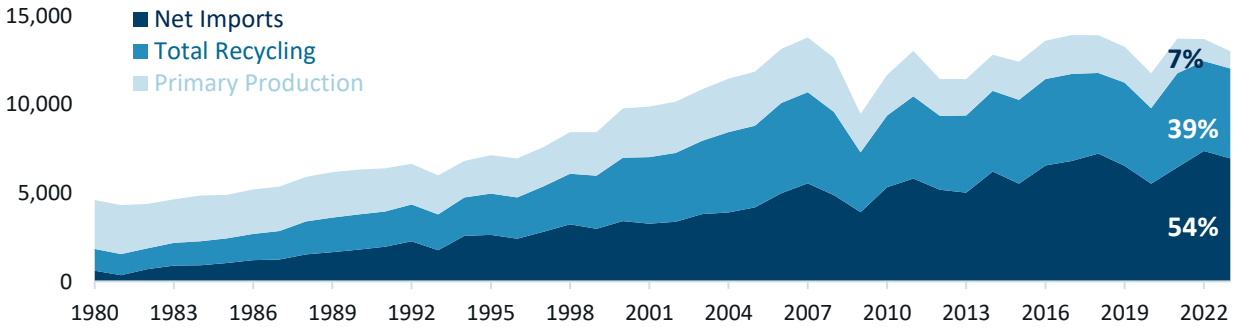
- Investing in advanced sorting technologies to improve scrap quality.
- Designing products with recyclability in mind.
- Encouraging the use of recycled content in new applications (European Aluminium, 2020).



Secondary aluminium production has been a key driver of sector decarbonisation from 2019 to 2023, with scrap recycling rates reaching record highs (Net Zero Industry Tracker, 2024). Focusing on Europe as an example, the use of secondary aluminium has steadily grown (Figure 4). However, rising demand has driven more low-cost imports, highlighting key barriers to scaling recycling in Europe:

- **Limited Scrap Availability**: Europe has been a net exporter of aluminium scraps since 2002, driven by the profitability of exports to other regions, lack of a strong business case for domestic processing, and relatively long lifespan of aluminium
- **Variable Scrap Collection Rates:** while Europe achieves a 70% collection rate, this remains inadequate and must rise to 90% globally by 2050 to support a circular economy
- **Quality & Processing Issues:** advanced sorting and purification technologies are needed to maximise post-consumer crap use, as primary aluminium remains superior for high-grade industrial applications
- **Downcycling:** aluminium is often a minor component in products, making recovery costly and repurposing recycled aluminium into lower-quality applications

Figure 4: European Aluminium Supply by Source
(kilo tonnes)



Source: European Aluminium

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Process Innovations

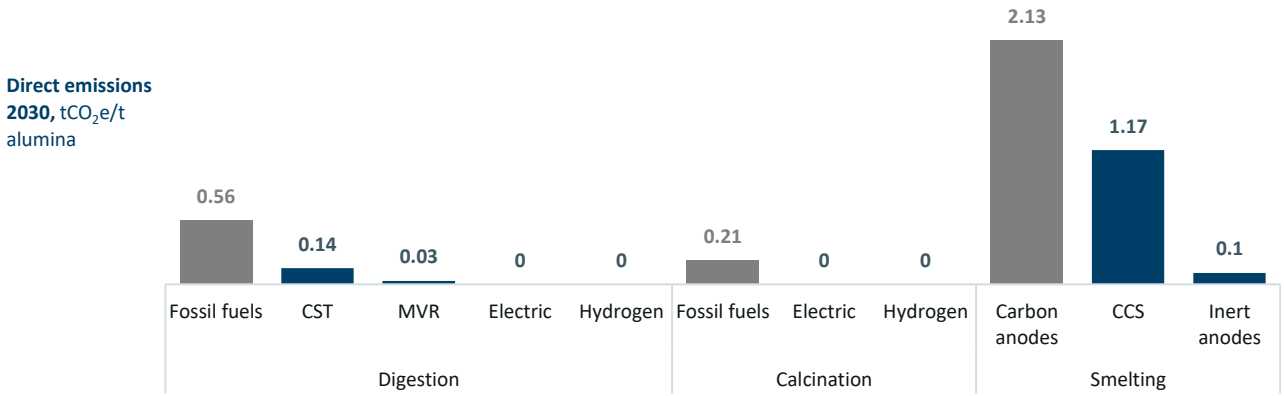
Addressing refining and smelting emissions is key to near-zero emissions:

- **Refining:** Technologies like electric boilers, mechanical vapour recompression (MVR), and concentrated solar thermal (CST) can significantly reduce emissions in alumina refining, though they face challenges like location feasibility and required R&D (Mission Possible Partnership, 2022).
- **Smelting:** Emerging solutions include inert anodes, which eliminate process emissions, and carbon capture & storage (CCS), capable of reducing CO2 emissions by 90%. However, these require further development and investment to be commercially viable (ELYSIS, 2022).

Process emissions from aluminium refining and smelting represent the majority of emissions in primary production, particularly during the digestion, calcination, and smelting stages, due to the significant amount of thermal energy and electricity required.

Although several technologies exist, a few at an advanced stage of development, Figure 5 shows that most are still in the conceptual or research phases. As a result, they are unlikely to be fully developed and commercially available until the end of the decade. Moreover, the widespread adoption of these technologies will face significant hurdles, including increasing prices for end-users due to high capital investments, ensuring equitable access across the industry, and securing supplies of low-carbon power and green hydrogen (Mission Possible Partnership, 2022).

Figure 5: Comparison of Digestion, Calcination, and Smelting Technologies



	Fossil fuels	CST	MVR	Electric	Hydrogen	Fossil fuels	Electric	Hydrogen	Carbon anodes	CCS	Inert anodes
Commercial Readiness Year	-	2027	2027	2020	2027	-	2030	2030	-	2030	2030
Technological Readiness Level	9	7	7	9	8	9	4-5	4-5	9	3-4	7

Source: Adapted from Mission Possible Partnership (Making Net Zero Aluminium Possible).

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Maximising Resource Efficiency

Improving material efficiency can further reduce emissions through:

- **Lightweighting:** Optimising product design to use less aluminium while maintaining performance.
- **Reducing Waste:** Minimising scrap during manufacturing processes.
- **Extending Product Lifecycles**: Designing repairable and durable aluminium products to lower demand for frequent replacements.
- **Repurposing:** Ensuring end-of-life aluminium is redirected into new applications to close the material loop (Circular Aluminium Action Plan, 2022).

Addressing the projected rise in aluminium demand by 2050 is critical, especially from key sectors such as transportation, construction, packaging, defence, and electronics. However, due to aluminium's unique properties, there remains no cost-effective substitutes and heavy reliance on primary aluminium production, making it essential for producers to optimise their manufacturing processes as outlined above.

Additionally, influencing consumption patterns of end users remains challenging, and greater awareness is needed to promote sustainable practices and closed-loop systems. Overcoming these barriers will require strong collaboration across the value chain, particularly between industry stakeholders and policymakers.

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5 Future Pathways and Recommendations

Decarbonising aluminium requires coordinated efforts from stakeholders across the industry. Actions must be tailored to short-, medium-, and long-term goals:

SHORT-TERM (2025-2030)

- Scale up low-carbon powered smelters.
- Enhance recycling rates and improve scrap collection systems.
- Implement energy efficiency measures in existing facilities.

MEDIUM-TERM (2030-2040)

- Deploy commercially ready inert anode technology.
- Expand the use of green hydrogen in refining and smelting.
- Build CCS infrastructure for high-emission facilities.

LONG-TERM (2040-2050)

- Establish a fully decarbonised aluminium value chain.
- Promote global collaboration on sustainable aluminium practices.
- Transition to a circular economy model where primary production is minimised supported by robust recycling systems.

6 Conclusion

The path to decarbonising aluminium production is challenging but achievable. By integrating low-carbon energy, advancing innovative technologies, and fostering circular economy practices, the industry can significantly reduce its carbon footprint while supporting global climate objectives. Collaboration among governments, industries, and civil society will be essential to accelerating this transition and ensuring the sustainability of this vital material.

The transition to a net-zero aluminium industry not only addresses environmental concerns but also unlocks opportunities for innovation, competitiveness, and long-term growth in a rapidly evolving global economy (IEA, 2021).

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Image Sources: Cover: Speira, Bauxite Mining: Getty Images, Refining: Healthy & Safety International, Smelting: Oil Price.com, Casting: IMARC Group, Low-Carbon Energy Integration: Tata Steel, Recycling and Circular Economy: Ghafari Petrochemical, Process Innovations: Mining.com, Maximising Resource Efficiency: FluIDect, Conclusion: Merus Power

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