NET-ZERO BY 2050:

# SCIENCE-BASED DECARBONISATION PATHWAYS FOR THE EUROPEAN ALUMINIUM INDUSTRY

November 2023

European Aluminium

ANYTHING BUT BASIC

# Executive **Summary**

The aluminium sector stands at a crossroads in the face of escalating global concerns surrounding climate change and greenhouse gas (GHG) emissions. As an energy-intensive and hard-to-abate industry, aluminium production is responsible for significant GHG emissions globally, generating more than 1.1 Gt$CO_2$e of emissions annually. At the same time, aluminium is recognised as an **essential material for the transition to a fully decarbonised economy** due to its properties, providing input material for a wide range of applications in our modern economy. Europe will therefore need large and increasing quantities of sustainably produced aluminium in order to achieve its wider climate and energy ambitions. For the European aluminium industry, responding to this need is both a matter of environmental stewardship and a strategic imperative to ensure its long-term competitiveness and viability.

This study aims to provide pathways for decarbonising European aluminium production by 2050. The industry has seen important improvements in terms of reduced climate impacts in the last decades, with noticeable emission abatements across the entire value chain. Nonetheless, meeting the targets set in the Paris Agreement and in the EU 2050 long-term climate strategy will require strong leadership and decisive action to further accelerate emissions abatements across the entire aluminium value chain in Europe.

In order to foster and plan these emissions reduction efforts, this study estimated the current $CO_2$e footprint of aluminium production in Europe, mapped the available and future decarbonisation options and technologies, and assessed the enabling conditions to concretise 1.5℃ aligned decarbonisation pathways for the European aluminium value chain segments and the entire European aluminium industry. The decarbonisation pathways were developed using a cost optimisation model. For this, carbon budgets tailored to each European aluminium value chain segment were identified.

**European aluminium production emitted about 24 Mt$CO_2$e in 2021**, which was chosen as the baseline year in the study. This figure includes direct emissions from process-related activities and on-site thermal energy generation, as well as indirect emissions from electricity use. Primary production accounts for around 75% of total production emissions, followed by recycling (15%) and semis-fabricated aluminium products (11%). In total, **this represents about 2.3% of emissions from the global aluminium industry**. When including imports, emissions from the European industry increase to 4.9% of the total global GHG footprint.

The analysis presented in this study demonstrates that decarbonising to remain within the 1.5℃ carbon budget allocated to the European aluminium industry, in a context of increasing demand for aluminium products, is possible but will require ambitious action. The pathways illustrate that **emission reductions of more than 90% can be achieved by 2050**. For key milestone years 2030 and 2040, the emissions profile of European aluminium production should be cut by at least 37% and 78%, respectively, compared to baseline levels. Rapid **decarbonisation of the electricity grid** plays a central role in achieving these ambitious reduction targets, combined with the **introduction of inert anodes in smelters** and **shifts to low-carbon furnaces and alternative heat systems** to reduce direct process emissions, as well as **increased scrap recycling**.

> The pathway illustrates that **emission reductions of more than 90% can be achieved by 2050.**

Furthermore, demand for low-carbon electricity in the European aluminium industry is expected to grow by around 82% between today and 2050.

Successful decarbonisation of European aluminium production requires significant actions from market players but also **decisive leadership from policymakers** to ensure that the necessary enabling conditions are put in place at the necessary speed and scale. First, efforts to ensure the secure and cost-competitive supply of **low-carbon electricity at the necessary capacity** must be a priority for European policymakers. As a second lever, boosting investments into R&D and facilitating the uptake of **low-carbon technologies** is crucial for effectively abating process-related emissions. Third, measures should be introduced to **increase the proportion of recycled aluminium**, including both upstream and downstream policies for improved material circularity.

The full decarbonisation of the European aluminium industry will also require significant emissions reductions from **imported aluminium products**. Mitigating emissions from European imports can be done by **tightening sourcing requirements** in line with intensity values established in the International Aluminium Institute's (IAI) 1.5°C scenario pathway. Another promising means of addressing import-related emissions is reducing the overall need for aluminium products from outside of Europe. To achieve this, policymakers must incentivise and support production capacity growth across the entire European supply chain. Ultimately, **increased aluminium production in Europe will help improve the region's material autonomy** while also eliminating significant emissions associated with carbon-intensive imports.

Mitigation of industrial GHG emissions has emerged as a pressing global imperative, and the European aluminium sector stands at the forefront of this transition. Aluminium will play a decisive role in achieving the targets of the Paris Agreement, but remaining within the 1.5°C allocated GHG budget until 2050 will pose significant challenges to the operators in the sector. To deliver on this roadmap, immediate and ambitious efforts are required from industry actors as well as policymakers.

# NET-ZERO BY 2050: SCIENCE-BASED DECARBONISATION PATHWAYS **FOR THE EUROPEAN ALUMINIUM INDUSTRY**

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# Contents

# Abbreviations

| | |
|---|---|
| °C | Degrees Celsius |
| **CAPEX** | Capital Expenditure |
| **CBAM** | Carbon Border Adjustment Mechanism |
| **CCS** | Carbon Capture and Storage |
| **CfDs** | Contracts for Difference |
| **$CH_4$** | Methane |
| **$CO_2$** | Carbon Dioxide |
| **$CO_2e$** | Carbon Dioxide Equivalent |
| **CST** | Concentrated Solar Thermal |
| **EA** | European Aluminium |
| **EFTA** | European Free Trade Association |
| **ETS** | Emissions Trading System |
| **EU** | European Union |
| **EVs** | Electric Vehicles |
| **GHG** | Greenhouse Gas |
| **GWP** | Global Warming Potential |
| **IAI** | International Aluminium Institute |
| **IEA** | International Energy Agency |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **LCI** | Life Cycle Inventory |
| **MPP** | Mission Possible Partnership |
| **MVR** | Mechanical Vapor Recompression |
| **OECD** | Organisation for Economic Co-operation and Development |
| **OPEX** | Operational expenditure |
| **PFCs** | Perfluorocarbons |
| **PPA** | Power Purchase Agreement |
| **R&D** | Research & Development |
| **SMEs** | Small and Medium-sized Enterprises |

# List of **Tables**

# List of **Figures**

# Table of **Definitions**

**Carbon Border Adjustment Mechanism (CBAM)**. EU regulation that imposes carbon pricing on imports of certain goods, including aluminium products, to prevent carbon leakage and ensure a level playing field for European industries.

**Carbon budget**. The amount of GHG emissions that can be released into the atmosphere while limiting global warming to a specific target, helping to manage and mitigate climate change.

**Carbon capture, utlilisation and storage (CCUS)**: Set of technologies to capture and use, or permanently store, $CO_2$ emissions produced from industrial processes or power generation. Use cases of captured $CO_2$ include producing synthetic fuels, fertilisers, chemicals, and $CO_2$-enhanced building materials.

**Carbon dioxide equivalent ($CO_2e$)**: Unit of measurement that represents the amount of GHG emissions released into the atmosphere in terms of their equivalent warming potential to carbon dioxide ($CO_2$) over a specified time period, usually 100 years. It is used to compare and aggregate the impact of different GHGs, each with its own global warming potential (GWP), on climate change.

**Decarbonisation pathway**. Trajectory outlining steps and measures to progressively reduce GHG emissions from a particular sector, industry, or region in order to achieve climate goals and transition to a low-carbon future.

**European Union Emissions Trading System (EU ETS)**. Cap-and-trade program established by the EU to limit GHG emissions from various industries, including aluminium, by allocating and trading emission allowances.

**GHG Protocol**. Framework for measuring, managing and reporting GHG emissions, established by the World Resources Institute and World Business Council for Sustainable Development.

**Paris Agreement**. Global treaty within the United Nations Framework Convention on Climate Change (UNFCCC) that aims to combat climate change by setting international targets for limiting global warming and promoting efforts to reduce GHG emissions.

**Power Purchase Agreement (PPA)**. A PPA is an electricity purchase agreement between two actors to secure long-term supply of renewable energy. In this study, only physical PPA are consider when referring to PPA. This includes the actual delivery of electricity, from a specific energy generating facility, to the buyer's location.

**Primary aluminium**. New aluminium metal produced from raw materials through the electrolytic process, also referred to as the aluminium smelting process.

**Scope 1, 2 and 3 emissions**: Common classification of GHG emissions established by the GHG Protocol. Scope 1 includes direct emissions from a company's own activities, mainly on-site fuel combustion and other process related emissions. Scope 2 covers indirect emissions from purchased electricity or heat. Scope 3 encompasses all other indirect emissions, including for example emissions from material extraction and production in supply chain, employee commuting, and product use.

**Secondary aluminium**. Recycled aluminium derived from pre- or post-consumer scrap, which is reprocessed to create new aluminium products. In this report, secondary and recycled aluminium are used interchangeably.

**Semi-fabricated aluminium**. Aluminium products that have undergone initial shaping or processing steps, such as rolling, extrusion, or forging, before being further fabricated into finished products.

# 1. Introduction

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## 1.1 Overview of this study

This document represents the final report of the project "Science-based decarbonisation pathways for the European aluminium industry". The project, running from March 2023 to September 2023, was commissioned by European Aluminium and performed by Ramboll Management Consulting (hereafter referred to as the Consultant).

In the context of a rapidly increasing Earth's temperature due to the greenhouse effect induced by rising concentrations of gases in the atmosphere such as carbon dioxide ($CO_2$), methane ($CH_4$), and perfluorocarbons (PFCs), so-called greenhouse gases (GHG), all emission reductions can contribute to mitigating the detrimental impacts of climate change. Tackling the climate challenge therefore requires decisive and rapid actions from all actors in society to reduce the greenhouse gas footprint of their activities. This includes requiring the industrial sector to decarbonise its operations.

According to the Intergovernmental Panel on Climate Change (IPCC)[1] net GHG emissions have increased since 2010 across all major sectors, with industry accounting for 22% of net global GHG emissions in 2019, corresponding to 13 $GtCO_2e$. Among the industrial sectors, the global aluminium industry is responsible for about 2% of global anthropogenic emissions, generating more than 1.1 $GtCO_2e$ of emissions annually[2]. Aluminium is traditionally considered a "hard to abate" sector, meaning that GHG emissions abatement is not straightforward as in other sectors of the economy due to lack of technology, or because its cost remains prohibitive.

While its production is responsible for significant GHG emissions globally, aluminium is recognised as an essential material for the transition to a fully decarbonised economy due to its properties. Besides being a highly circular material, which can be recycled multiple times without losing its properties, aluminium plays an increasing role in reducing the climate footprint of other sectors. This is for example the case in the road transport sector, where aluminium is increasingly being used as body construction material to reduce the energy consumption of electric vehicles (EVs) due to its lightweight, or for manufacturing battery pack enclosures due to its thermal conductivity and durability.

It therefore becomes paramount to identify the most efficient and viable ways to decarbonise aluminium's production and recycling following emission reduction pathways in line with the latest indications from the scientific community. Specifically, this requires a detailed analysis of the decarbonisation options and technologies which can be adopted to reduce the GHG footprint of the various segments of the aluminium value chain, taking into account the expected steady growth in the global demand for aluminium in the coming decades.

Besides being a highly circular material, which can be recycled multiple times without losing its properties, aluminium plays an increasing role in reducing the climate footprint of other sectors.

[1] IPCC (2023). Synthesis Report of the IPCC Sixth Assessment Report (AR6). Available at: https://www.ipcc.ch/report/ar6/syr/
[2] World Economic Forum (2020). Aluminium for Climate: Exploring pathways to decarbonise the aluminium industry. Available at: https://www3.weforum.org/docs/WEF_Aluminium_for_Climate_2020.pdf

In this sense, the aluminium sector has been the focus of attention for a number of initiatives across its value chain aimed at defining technological options and a sector transition strategy to reach net zero emissions. Most notably, the International Aluminium Institute (IAI) and the Mission Possible Partnership (MPP) have looked into providing a vision for the industry's low-carbon future at the global level. Yet, region-specific emission and technological pathways, aligned with the 1.5°C target and reflecting the local industry configuration, are still missing.

The European aluminium sector has seen important improvements in terms of reduced climate impacts in the last decades, with noticeable emission abatements both within primary aluminium production as well as semi-fabrication and recycling processes. With the aim of remaining at the forefront of sectoral decarbonisation, the industry is now looking into the available solutions to further reduce its environmental impact.

In order to foster and plan the emissions reduction efforts of the European aluminium industry, while maintaining its leadership at the global level and proving to customers and stakeholders its strong commitment towards the future, this study estimated the current $CO_2$e footprint, mapped the available and future decarbonisation options and technologies, and assessed the enabling conditions to concretise 1.5°C aligned decarbonisation pathways for the European aluminium value chain segments and the entire European aluminium industry.

## 1.2 Objectives of this study

With the aim of supporting the European aluminium industry in reducing its greenhouse gas emissions and demonstrating its commitment, this study was aimed at **defining science-based regional decarbonisation pathways for the European aluminium industry**. Specifically, the study had the following key objectives:

- Define and showcase the commitment of the European aluminium industry to decarbonise its operations towards the year 2050, in line with the IPCC's 1.5°C scenario.
- Complement the positive information linked to the benefits of aluminium in use[3] with a robust perspective on the production and manufacturing stages of the value chain.
- Characterise the sectoral framework under which member companies of European Aluminium can define their specific decarbonisation pathways, also supporting them in answering the requests from customers and stakeholders.
- Identify recommendations to policymakers, in terms of instruments and investments, with the aim to create the necessary enabling conditions for the sectoral decarbonisation pathways to bring the European aluminium industry on a 1.5°C aligned trajectory.

## 1.3 Overview of this report

This report is organised into the following chapters:

- Executive Summary.
- **Chapter 1 - Introduction**. Introduces the study and its main objectives.
- **Chapter 2 - Background and Context**. Provides an overview of the European aluminium sector, its value chain, and its journey towards carbon neutrality.
- **Chapter 3 - Methodological Approach**. Summarises the applied methodological framework including data collection and assumptions.
- **Chapter 4 - Results**. Presents the main findings of the analysis including the $CO_2$ footprint and the pathways to decarbonise the European aluminium industry in line with the 1.5°C target.
- **Chapter 5 - Discussion and Policy Recommendations**. Presents the policy recommendations suggested to support the decarbonisation of the European aluminium sector.

[3] Read more about the role of aluminium in the energy transition in 'Aluminium, the Base Metal for the Green Transition'. European Aluminium (2023). Available at: https://online.fliphtml5.com/wvryv/egku/#p=1

# 2. Background and **Context**

# 2. Background and **Context**

The aim of this chapter is twofold. Firstly, it provides an overview of the aluminium sector and its value chain, covering all segments of its supply value chain and the demand side. Secondly, it introduces the state of the European aluminium industry and how this has evolved over the last two decades across primary and secondary aluminium production.

The chapter also briefly introduces the context in which the European aluminium industry is operating. Specifically, how EU decarbonisation policies influence its operations and target setting.

## 2.1 The aluminium sector and its value chain

### 2.1.1 Aluminium properties and uses

Aluminium is a highly versatile metal which progressively became an essential material in modern society thanks to its physical properties, and it is now widely used in various industries such as transportation, construction, packaging, and electrical engineering. Some of the properties that led to its wide adoption include:

- **Versatility**, as it can be cast, melted, formed, and extruded to be manufactured into a variety of shapes and then fabricated for a whole variety of uses.
- **Lightweight**, with a density of 2.71 g/cm$^3$ corresponding to a third of that of steel[4]. This property makes it attractive for applications where weight reduction is desired, such as in transportation and aerospace industries.
- **Corrosion resistance**, since aluminium has a natural oxide layer on its surface, which provides inherent corrosion resistance. Additional surface treatments such as painting and anodising can further improve the resistance to corrosion.
- **Electrical and heat conductivity**, as aluminium is an excellent heat conductor and a good electrical conductor. For this reason, it is often used as a key material for power transmission lines, electrical products, and heat exchange applications.
- **Reflectivity**, since aluminium has a high reflectivity for both light and heat radiation, makes it widely used in reflective surfaces, such as mirrors, solar reflectors, and heat shields.
- **Odourless and water resistant**, making it a good material for packaging of food and pharmaceuticals, protecting them from oxygen and light.
- **Recyclability**, as aluminium can be recycled endlessly without losing its original properties.

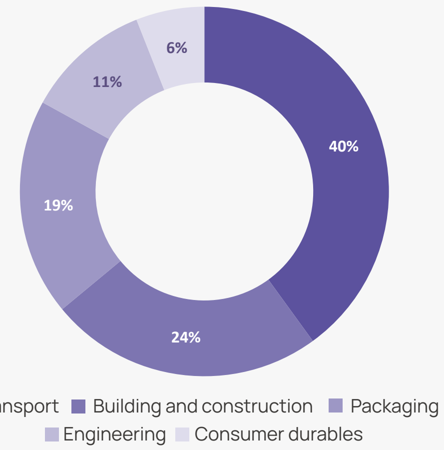
Considering its properties, it is not surprising to see that aluminium finds usage in multiple industries. Transport and Construction, in particular, are major end-use sectors of aluminium, and together represent about 65% of the aluminium demand as shown in the **figure below**. These sectors are followed by Packaging and Engineering with 19% and 11% of end use demand each, while the remaining 6% is found within Consumer Durables.

[4] Kolbeinsen L. (2020). The beginning and the end of the aluminium value chain. Matériaux & Techniques 108, 506. Available at: https://doi.org/10.1051/mattech/2021008

Some of the most common uses of aluminium across end use sectors include:

- To produce **Transport** vehicles such as cars, trucks, aircrafts, trains, ships, and bicycles, allowing improvements in fuel efficiency and reduced emissions due to their lightweight.
- For the realisation of structural components in the **Construction** industry, including window frames, doors, roofing systems, curtain walls, and facades. Its malleability also makes it a useful material for architectural applications.
- For the production of recyclable **Packaging** such as cans for beverages and food, foil for wrapping, and containers.
- To manufacture **Electrical Components** such as transformers, capacitors, electrical transmission lines, wiring and conductors.
- To produce industrial **Machinery and Equipment** including frames, storage tanks, and process piping.

Figure 1. End use of aluminium in Europe



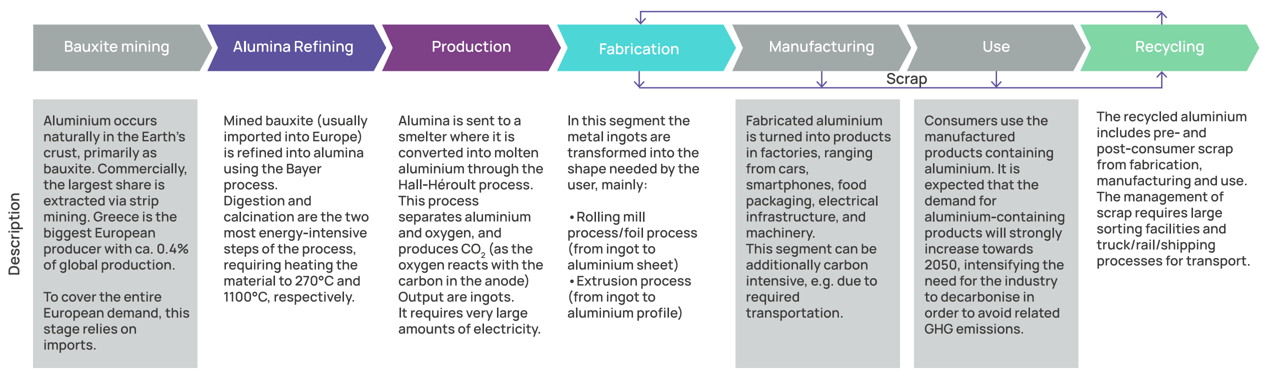

Source: European Aluminium

## 2.1.2 The aluminium value chain

Aluminium production is often described as a process of mining, refining, smelting, transformation and recycling, as it involves a complex value chain encompassing several stages, from the extraction of raw materials to the manufacturing of finished products. In general, it is possible to distinguish between primary aluminium production, involving the production of new aluminium products from raw materials, and secondary aluminium production, which involves recycling aluminium scrap to form new products.

The **figure below** summarises the main steps in the aluminium value chain[5].

Figure 2. The aluminium value chain




Source: Ramboll.

[5] The segments highlighted in grey are not within the scope of this study.

## Primary aluminium production

While aluminium is one of the most commonly occurring elements on Earth, it rarely occurs in nature in its pure form since it is highly reactive and bonds to other materials. The most common form of aluminium in nature is an ore known as **bauxite**, which therefore needs to be **extracted** and refined. Bauxite is typically found in tropical or subtropical regions and is extracted through open-pit mining or underground mining methods. According to the United States Geological Survey (USGS)[6], most of the bauxite resources are distributed in Africa **(32%)**, Oceania **(23%)**, South America and the Caribbean **(21%)**, Asia **(18%)**, and elsewhere **(6%)**. In 2021, the major producing countries were Australia **(110,000 kt)**, China **(86,000 kt)**, and Guinea **(85,000 kt)**. In Europe, the largest producer is Greece with approximately 1,500 kt of bauxite in 2020, corresponding to 0.4% of global production.

Once the bauxite has been extracted, it is then transported to **refineries** for further processing. The ore bauxite is purified to yield aluminium oxide, also known as **alumina**, using the Bayer process, a standard method developed in the late 19th century and named after its inventor Karl Bayer. In this process, the bauxite is first washed and then crushed and ground into a fine powder. It is then dissolved with caustic soda at high temperatures (digestion). The resulting product is washed, filtered, and calcined to remove impurities. The final result is a white powder (alumina), which can then be transferred to aluminium smelters or used as input in the chemical industry.

Alumina is sent to an **aluminium smelter** where it is converted into molten aluminium through the Hall-Héroult process, the most widely used method for aluminium smelting developed by Charles Martin Hall and Paul Héroult in the late 19th century. Smelting is the process of extracting pure aluminium metal from alumina through electrolysis in a carbon-lined cell, resulting in aluminium that is more than 99% pure. Specifically, alumina is dissolved in a molten bath of cryolite at about 960°C and is subjected to high electric current (electrolysis). As a result, liquid aluminium deposits at the cathode, while at the anode oxygen combines with carbon from the anode to form carbon dioxide. The liquid aluminium is finally refined to remove impurities and cast into extrusion ingots, sheet ingots, or foundry alloys, or cast into special molds to be remelted at a later stage.

After the smelting process, the aluminium ingots can be purchased by downstream operators to produce **semi-finished products** (also called "wrought aluminium", "semis", or "mill products") which are then used as key inputs for end-use sectors such as automotive, construction, packaging and aerospace. These downstream operators include, notably, rollers, extruders, and casters, which together account for 90% of the EU's production of aluminium semi-finished products[7]. **Casting** consists in first allowing foundry alloys to melt in a furnace and then pouring the molten metal into a mould where it solidifies. Aluminium castings are produced in various shapes and alloys for a large variety of applications. **Rolling** involves passing the sheet ingots through a series of rollers to reduce thickness and improve the surface finish. This process is commonly used in the production of foil, plates, cans, and other flat products. Finally, **Extrusion** involves heating the aluminium ingot and pressing it through a shaped tool called a die to create profiles with complex cross-sections, such as window frames, tubing, and structural components.

Fabricated aluminium is then turned into products in factories of end-use sectors to **manufacture final products**, ranging from cars, smartphones, food packaging, electrical infrastructure, and machinery. The final aluminium product can then be sold to final consumers and **used**.

> **The most common form of aluminium in nature is an ore known as bauxite**, which therefore needs to be extracted and refined.

[6] United States Geological Survey (2022). Bauxite and Alumina. Available at: https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-bauxite-alumina.pdf
[7] Cassetta et al. (2019). The European Union Aluminium Industry. The impact of the EU trade measures on the competitiveness of downstream activities. Available at: https://face-aluminium.com/wp-content/uploads/2019/06/2019-LUISS-Study.pdf

# Secondary (recycled) aluminium production

Secondary aluminium production refers to the production of aluminium from **recycled aluminium** originating from various forms of aluminium scrap, including for example aluminium sheets, cast aluminium, extrusions, or final products containing aluminium (e.g. cans, wires, automobiles, etc.). In addition to scrap, other aluminium-containing process waste such as dross and skimmings is used as input for recycling. In recycling, aluminium scrap is collected and sorted based on its alloy composition, melted in a furnace at high temperature, typically around 660-700℃, turned into molten aluminium, and then refined and used to cast new products.

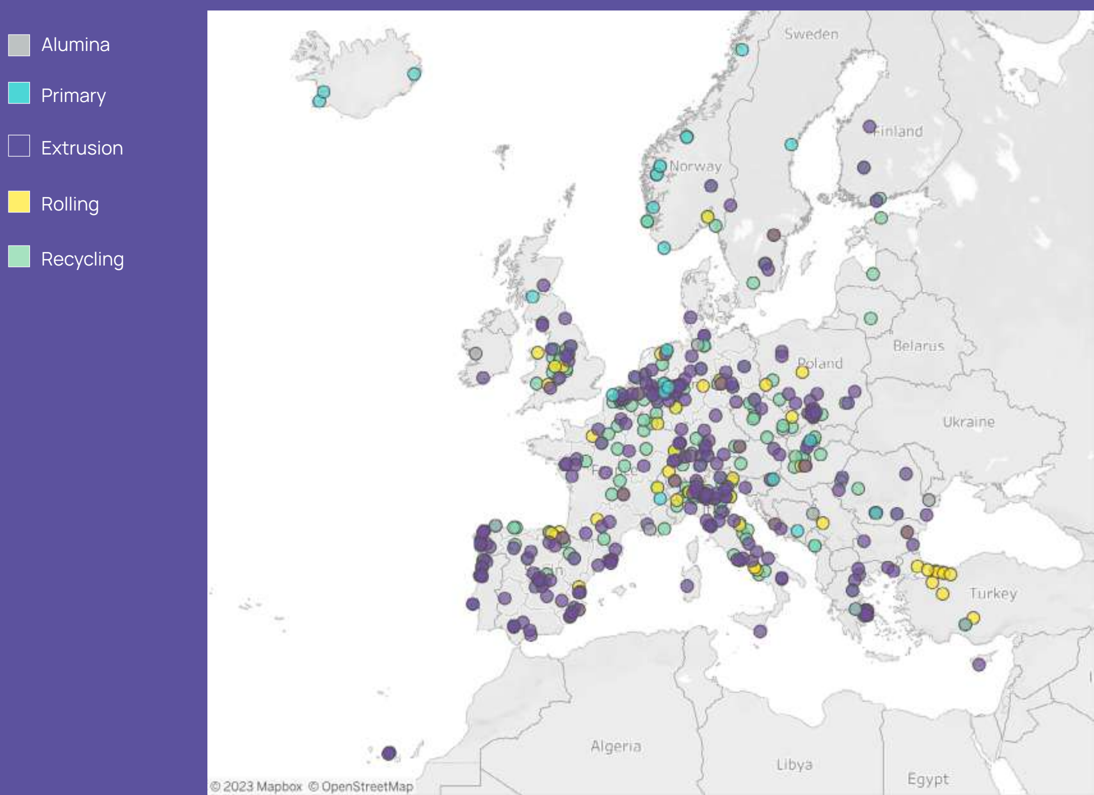
A distinction is usually made between refining and remelting of recycled aluminium, based on the respective output: cast alloys for the former, wrought alloys for the latter.

Compared to primary aluminium production, secondary production allows up to 95% energy and GHG emissions savings[8].

## 2.2 The European aluminium industry

In total, more than 600 aluminium plants are located in the EU and its neighbouring countries, as depicted in the picture below. Currently, however, the European aluminium industry is mostly an industry of semi-finished products and recycling, with only five alumina refining plants and less than 20 smelters in the EU27, UK and EFTA regions together.

Figure 3. The location of plants by value chain segment in Europe



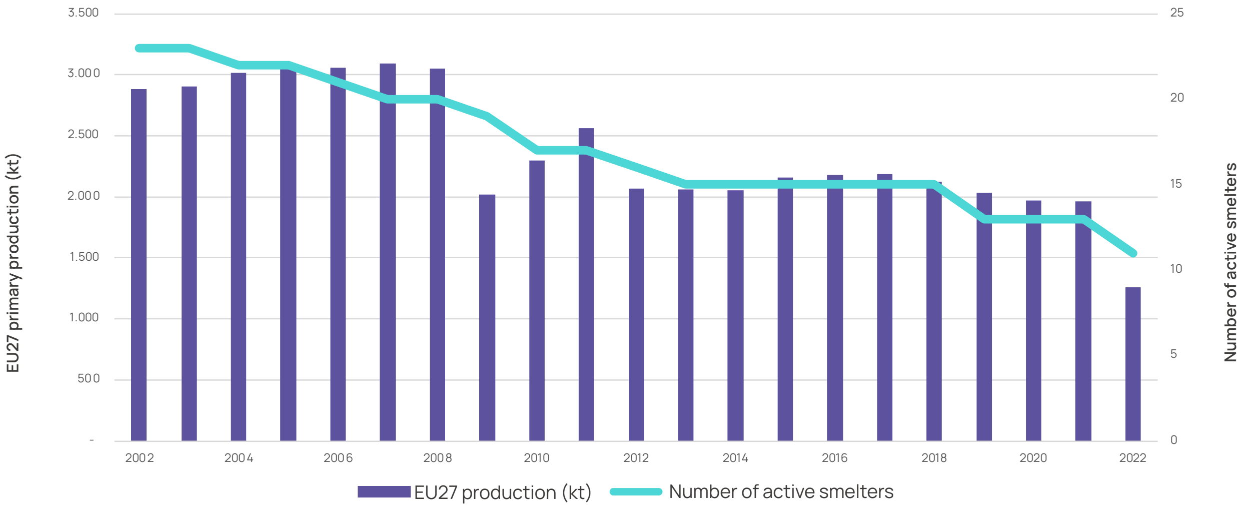

Source: European Aluminium.

[8] European Aluminium (2019). Vision 2050. European Aluminium's contribution to the EU's mid-century low-carbon roadmap. Available at: https://european-aluminium.eu/wp-content/uploads/2022/10/sample_vision-2050-low-carbon-strategy_20190401.pdf

### 2.2.1 Production of primary aluminium

The European aluminium sector covers approximately 6% of global primary aluminium production[9], with about half of production coming from the EU and the remaining half from European Free Trade Association (EFTA) countries[10]. Since 2008, the EU's primary aluminium capacity shrank by 30%, with some producing countries, such as Spain, Italy, the UK, and the Netherlands, that significantly curtailed or definitively ceased their production. The energy crisis in 2022 imposed further pressure on smelters due to the skyrocketing electricity prices, resulting in production cuts and permanent closure of plants[11]. The shrinking number of primary aluminium production plants, and the resulting decline in European production has led to a rising import dependency to meet primary demand.

Figure 4. Evolution of EU27's primary aluminium production and capacity



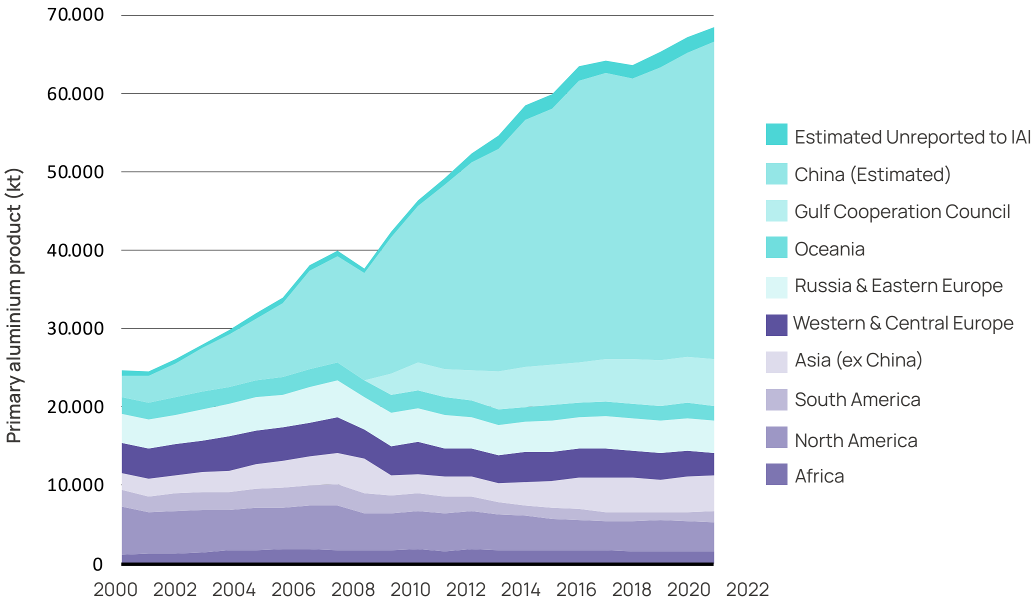

Source: European Aluminium.

Since primary aluminium production is a highly energy-intensive process, a major factor determining the choice of where to locate smelters is the need to access abundant, cheap, and reliable energy[12]. According to IAI data[13], on average between 13,500 and 16,700 kWh of energy is required to produce 1 tonne of primary aluminium, with variations across regions depending on the efficiency of the smelter. Energy costs and related GHG emissions also vary substantially across regions, depending on the specific source of energy providing electricity to the smelter, but also on the regulatory costs (costs for emitting GHGs, carbon taxes etc.) Smelters in North and South America, Russia and in EFTA countries (particularly Norway and Iceland) tend to rely on electricity sourced from hydropower, while smelters in other countries tend to rely on electricity generated from fossil fuels. In the Middle East, smelters heavily rely on the local reserves of natural gas, while smelters in countries like China, India, and Australia source their electricity from coal-fired power plants[14].

The geographical positioning of primary aluminium production has changed significantly since the early 2000s. China has become the world's leader in primary aluminium production at the detriment of Europe and North America. While China's production increased by more than 14 times, primary production in North America and in Western and Central Europe decreased by 38% and 23%, respectively. This is well depicted in the figure below[15].

[9] European Aluminium (n.d.). Industry & Market Data. Available at: https://european-aluminium.eu/about-aluminium/aluminium-industry/
[10] ERCST (2021). The aluminium value chain and implications for CBAM design. Available at: https://ercst.org/the-aluminium-value-chain-and-implications-for-cbam-design/
[11] Permanent closures of smelter facilities have been announced in Germany, the Netherlands, Slovenia and Slovakia.
[12] Cassetta et al. (2019). The European Union Aluminium Industry. The impact of the EU trade measures on the competitiveness of downstream activities. Available at: https://face-aluminium.com/wp-content/uploads/2019/06/2019-LUISS-Study.pdf
[13] International Aluminium Institute (2022). Statistics on Primary Aluminium Smelting Energy Intensity. Available at: https://international-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/
[14] OECD, 2019. Measuring distortions in international markets: the aluminium value chain. OECD Trade Policy Pap. Available at: https://doi.org/10.1787/c82911ab-en
[15] No data is reported for the Gulf Cooperation Council prior to 2010.

Figure 5. Primary aluminium global production by region

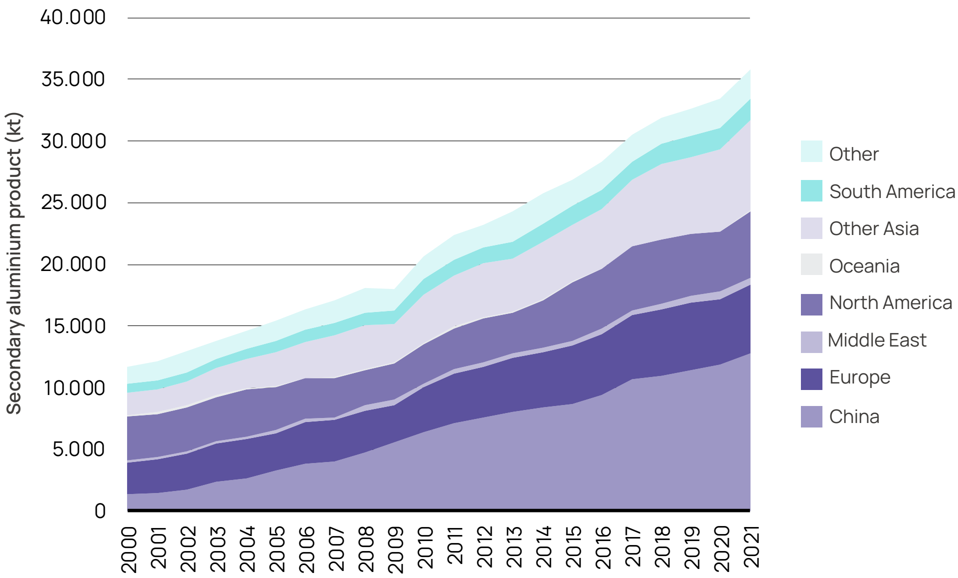



Source: IAI.

## 2.2.2 Production of secondary aluminium

When looking at secondary production, almost 36,000 kt of recycled aluminium were produced globally in 2021[16] **(Figure 6)**. Similarly to the primary aluminium case, China is by far the largest producer with more than 12,000 kt produced (about one-third of the annual global total), followed by other Asian countries (21%), Europe (15%), and North America (15%). Contrary to the primary aluminium case, secondary production has been increasing across all regions in the last 21 years, with the only exception of Oceania which experienced a 70% decrease compared to the year 2000.

Figure 6. Recycled aluminium production by region




Source: IAI Global Aluminium Cycle.

According to European Aluminium[17], there are about 220 recycling plants in Europe, most of which are small and medium-sized enterprises (SMEs).

[16] IAI (2023). Global Aluminium Cycle. Available at: https://alucycle.international-aluminium.org/public-access/public-global-cycle/
[17] European Aluminium (2015). Recycling aluminium: A pathway to a sustainable economy. Available at: https://issuu.com/europeanaluminium/docs/recycling-aluminium-2015

## 2.3 EU decarbonisation policy and its impact on the sector

As mentioned in previous sections, the aluminium industry is responsible for a non-negligible share of GHG emissions globally. The electrochemical processes involved in the primary aluminium production generate direct emissions of $CO_2$ and PFCs, while indirect emissions from electricity demand during smelting represent the largest part of the primary aluminium GHG footprint. The transformation of primary aluminium into semi-fabricated products and the recycling of scrap metal also result in direct and indirect emissions, but these are significantly lower compared to the emissions embodied in primary aluminium production.

Being an energy-intensive and hard-to-abate sector, the European aluminium industry plays a pivotal role in reducing GHG emissions and achieving the net-zero emissions target set by the EU in 2050. While the EU aluminium industry already successfully reduced the GHG footprint of its primary aluminium production[18], meeting the targets set in the Paris Agreement and in the EU 2050 long-term strategy will require even more decisive action to abate emissions across the entire aluminium value chain.

European climate mitigation policies collectively shape the operating environment of the European aluminium industry. On one hand, the industry faces challenges in meeting emissions reduction targets and in implementing the necessary technological and operational changes. On the other hand, it also presents opportunities for innovation, improved resource efficiency, and sustainable growth. The aluminium industry in Europe has so far been proactive in responding to decarbonisation policies, investing in R&D, adopting cleaner technologies, and working towards sustainable practices to preserve its competitiveness and alignment with European climate goals.

Besides providing a solid, clear regulatory framework, EU decarbonisation policies also indirectly influence the pace at which the sectoral decarbonisation can happen. The greening of the European power mix, in particular, represents a necessary condition for aluminium producers to access cheap and clean electricity to reduce their GHG footprint.

> The European aluminium industry plays a pivotal role in **reducing GHG emissions and achieving the net-zero emissions targets set by the EU in 2050.**

[18] European Aluminium (2019). Vision 2050. European Aluminium's contribution to the EU's mid-century low-carbon roadmap. Available at: https://european-aluminium.eu/wp-content/uploads/2022/10/sample_vision-2050-low-carbon-strategy_20190401.pdf

# 3. Methodological **Approach**

# 3. Methodological **Approach**

The aim of this chapter is to provide an overview of the methods used in this study. The steps taken to conduct the study are presented and the main data inputs, assumptions and considerations are explained.

The decarbonisation pathways were developed using a cost optimisation model, which was constrained by carbon budgets tailored to each segment of the aluminium value chain in Europe. Inputs to the model were, among others, the GHG footprint of European aluminium value chain segments, the projected production volumes between 2022-2050, and electricity grid forecasts.

## 3.1 Overall methodological approach

This study aims to develop decarbonisation scenarios for each aluminium value chain segment as well as pathways towards a net-zero European aluminium industry in 2050. The methodological approach followed the steps illustrated in **Figure 7**.

Figure 7. Overview of methodological approach


Source: Ramboll.

The process involved several workshops with members of European Aluminium and expert interviews, to help validate assumptions and input data and to ensure findings in line with industry best practice.

## 3.2 Define the current GHG footprint of the European aluminium industry

First, a GHG emissions baseline for the European aluminium industry was established. This was done to help improve the understanding of current emission hotspots in the European context, and to generate data required for developing the decarbonisation pathways. The GHG footprint was calculated both for the aluminium industry as a whole and for each value chain segment. This level of granularity allowed for a thorough assessment of segment-specific emissions and their corresponding reduction pathways towards a net zero aluminium sector.

Every few years, European Aluminium compiles comprehensive and robust industry data, including life cycle inventory (LCI) data for the European aluminium industry, covering EU27, UK and EFTA (Norway, Iceland, Switzerland). The most recent data for the purpose of this study covers 2021, and the baseline year was chosen accordingly.

A material flow analysis was conducted for each segment in scope of this study[19], including data on European and global primary production and recycling volumes, and imports to Europe. Since the focus is on decarbonising aluminium production, only energy and emissions data directly related to these processes were considered. Data describing the thermal and electric energy use in production (Scope 1 and Scope 2) was collected per segment, as well as direct process-related emissions, and emissions of PFCs (Scope 1) from the aluminium smelting (electrolysis) process were also included. This differs from the scope used in IAI's emissions footprint calculations and European Aluminium's Environmental Profile Reports, which also include Scope 3 emissions from the use of ancillary materials and transport[20].

Following the data collection, emission intensities were calculated split by segment and production location (produced in Europe, imported to Europe or global average) and expressed in $CO_2e$ per tonne of aluminium ($CO_2e$/t Al). Since production methods and the source and use of energy vary between Europe and the rest of the world, the emission intensities for European aluminium production differ compared to imported products, which in turn may differ from the global average.

The GHG footprint of each value chain segment was estimated by multiplying production volumes (adjusted to t Al) with the corresponding emission intensity. These were then summed to find the total GHG footprint of the European aluminium industry. To allow for comparison and to determine Europe's share of the global carbon budget, values for the global aluminium industry were calculated following the same bottom-up approach. Due to limited availability of LCI data at the necessary level of granularity, emission intensities for global semi fabrication and recycling segments were based on the European intensity figures.

For Europe[21], data for 2021 provided by European Aluminium was used. It is important to note that this data represents the production weighted average value for aluminium processes in Europe, and that values for specific European countries or regions may therefore differ from what is stated in this report. Data on the global level and energy use for European imports were collected primarily from the IAI's 2019 Life Cycle Inventory report[22] as well as the Alucycle website[23]. Energy use values for European imports do not cover the full EU27, UK and EFTA region but are based on a coverage of the selected number of countries included in the 2019 IAI data for Europe[24]. Key assumptions on emission factors and conversion rates can be found in the Annex.

[19] The following segments are in scope: Bauxite mining, alumina refining, aluminium smelting, anode/paste production, primary casting, sheet production, extrusion and recycling (remelting and refining).
[20] International Aluminium Institute (2023). Greenhouse Gas Emissions – Aluminium Sector. Available at: https://international-aluminium.org/statistics/greenhouse-gas-emissions-aluminium-sector/
[21] EU27, the UK and EFTA countries (Iceland, Norway, Switzerland).
[22] International Aluminium Institute (2019). 2019 Life Cycle Inventory (LCI) Data and Environmental Metrics. Available at: https://international-aluminium.org/resource/2019-life-cycle-inventory-lci-data-and-environmental-metrics/
[23] International Aluminium Institute (2023). Global Aluminium Cycle. Available at: https://alucycle.international-aluminium.org/
[24] Germany, Greece, France, Iceland, Norway, Spain, and Sweden.

## 3.3 Projections and forecasts

In order to inform the analysis of the future European aluminium industry and the design of a 1.5℃ aligned decarbonisation path, forecasts on the European electricity grid and production and recycling levels in Europe between 2022-2050 were developed. The method for developing this forecast and projections is described in further detail below.

### 3.3.1 Electricity grid developments

Understanding how the electricity system will evolve until 2050 is instrumental for designing the decarbonisation pathways, as it impacts the cost and the emissions associated with different technology options. For this study, the Balmorel model[25] was used to simulate developments of the electricity grid, including the composition of grid electricity per source, future grid mix emission intensity, and levelized cost of energy or electricity per source in Europe. The model optimises future energy system design based on matching supply and demand at the lowest possible cost. It has been used in several peer-reviewed studies since the year 2000. It is an open-source project adjusted by Ramboll Energy Systems experts allowing to review and benchmark internally developed models. Assumptions on future demand are determined through national targets and publicly announced energy needs. Other key assumptions, including fuel prices, carbon taxes and existing generation and transmission capacities are based on forecasts from internationally recognized agencies and intergovernmental bodies such as the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC).

There is significant uncertainty associated with electricity grid forecasts. To allow for different development routes of the future electricity grid, and the possibility of performing a sensitivity analysis of the results, four future scenarios were simulated from the Balmorel energy model, see **Table 1**. When designing the aluminium industry decarbonisation pathways, the Economic Decarbonisation (EDE) was employed.

As seen in **Figure 8**, the forecasted rate of reduction of the European electricity grid emissions in the EDE follows closely scenarios from IEA[26] and the Federation of the European Electricity Industry, Eurelectric[27].

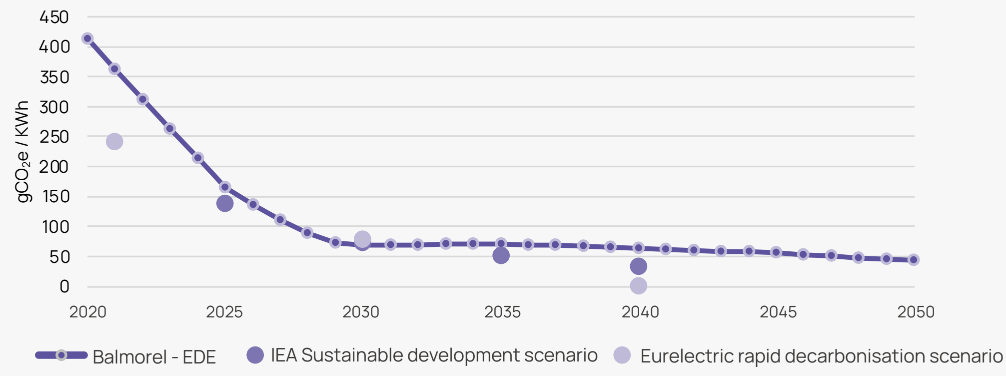
Table 1. Forecasting electricity grid developments – four scenarios based on Balmorel

| Scenario | Description |
|---|---|
| **Business as usual scenario (BAU)** | Represents the raw competitiveness of electricity generation technologies by excluding all policies related to a possible increased carbon price, national carbon taxes and EU-ETS developments.<br>Carbon price is set conservatively at EUR 5.93 per ton of $CO_2$, a value far under the current market price under the EU-ETS. |
| **Fuel volatility price scenario (FVR)** | This scenario seeks to address how unforeseen circumstances (like the war in Ukraine) will impact the green transition, and how much of an influence fuel prices have on the optimal investment decisions.<br>Assumes elevated fuel and natural gas prices 2022 to 2028. |
| **Economic decarbonisation scenario (EDE)** | This represents the scenarios identified as most likely. It projects carbon tax prices continue to increase, reaching approximately EUR 140 per ton $CO_2$ in 2030. Further, equity risk and discount risks are accounted for based on differences among technology and risks associated with each country. |
| **Optimistic decarbonisation scenario (OPT)** | Represents the impact of additional investments into green energy technologies driven by policy, which accelerates the decarbonisation of the grid but not at the lowest costs. This results in a rapid roll-out and increased capacity from offshore wind and hydrogen production. |

Source: Ramboll.

[25] The Balmorel energy model is a partial equilibrium model, developed for the purpose of modelling and analysis of the energy sector.
More information is available here: https://www.sciencedirect.com/science/article/pii/S2211467X18300038
[26] IEA (2020). Sustainable Development Scenario.
Available at: https://www.iea.org/data-and-statistics/charts/carbon-intensity-of-electricity-generation-in-selected-regions-in-the-sustainable-development-scenario-2000-2040
[27] Eurlectric (2022). Power Barometer 2022. Available at: https://powerbarometer.eurelectric.org/

Figure 8. EDE scenario compared to scenario forecasts from IEA and Eurelectric




Source: Balmorel energy model, IEA and Eurelectric.

### 3.3.2 Primary production, recycling, and imports of the European aluminium industry

The starting point for determining primary production and recycling volumes of the European aluminium industry in 2050 was IAI's projections on future global aluminium demand, which are based on a detailed and academically peer-reviewed material flow analysis[28]. More specifically, the IAI 1.5°C scenario (low substitution) was chosen since it incorporates a trajectory resulting in near zero emissions by 2050. Main assumptions under this scenario are a 4% total growth in primary aluminium production between 2020-2050, a 245% growth in secondary aluminium production based on the condition that all end-of-life aluminium is recycled[29] and advances in resource and material efficiency, limiting the growth of total aluminium demand over the period, compared to a business-as-usual scenario. Further, global aluminium demand is expected to grow by 50% by 2050 in this scenario, compared to 2020 levels.

As part of their analysis, IAI developed regional demand forecasts, including predictions on future primary production, recycling and import volumes. According to the IAI analysis, the European aluminium industry will see a 30% increase in demand by 2050, reaching 17,200 kt. Further, the IAI scenario for Europe predicts stable volumes of primary production and imports from 2022 onwards, meaning that the growing demand for aluminium in Europe will be covered by an increase in secondary production.

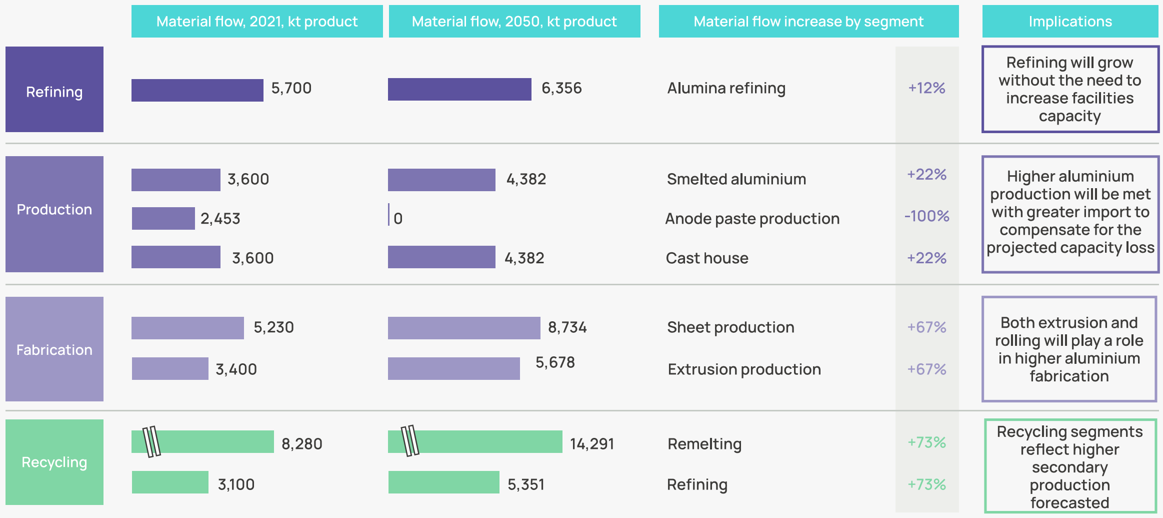
Building on IAI's regional scenario, an alternative scenario was developed to allow for increased primary aluminium production and reduced import dependency in Europe. In this scenario, the chosen compound annual growth rate (CAGR) for primary aluminium is 1.01%, which is the average between IAI's near zero growth scenario and the 2.02% expected average CAGR of key market sectors of aluminium between 2020-2050[30]. This then served as the basis for determining recycling volumes[31] during the same period, using the 30% increase in demand combined with the additional primary production as overall constraint.

Three regional scenarios were thus forecasted: 1) the IAI's zero growth in primary production scenario, 2) an optimistic 2.02% CAGR in primary production until 2050 scenario and 3) a 1.01% CAGR until 2050 scenario (medium growth scenario). In all scenarios, import volumes are expected to decrease significantly and rising demand for aluminium to be covered by growth in secondary production. The analyses presented in this report are based on the medium growth scenario.

[28] Mission Possible Partnership (2023). Making Net Zero Aluminium Possible – technical appendix.
Available at: https://missionpossiblepartnership.org/wp-content/uploads/2023/03/MPP-Aluminium-Technical-Appendix.pdf
[29] Full recycling based on 100% collection rate; losses are only due to physical limitations of the material.
Will require further investments in R&D for purifying scrap aluminium to meet the demand for low levels of alloyed aluminium.
[30] CM Group (2020). Global Megatrends and Regional and Market Sector Growth Outlook for Aluminium Demand.
Available at: https://international-aluminium.org/resource/cm-group-global-megatrends-and-regional-and-market-sector-growth-outlook-for-aluminium-demand/
[31] As product lifetimes differ, the future availability of secondary aluminium has a delayed correlation with the use of aluminium in different product categories. Such effects are not considered in this study.

In order to develop forecasts per value chain segment, the split in production and the share of European production and imports for each segment were matched with the overall primary and secondary production forecasts of the medium growth scenario. Segment-specific trends and drivers impacting production and import volumes in Europe were identified and quantified based on impact and timeframe. Building on this assessment, the proportion of European production and imports was modified for each value chain segment. Finally, the overall increase in material flows between 2021-2050 was calculated, as shown in **Figure 9**. For anode/paste production, the material flow in 2050 is expected to be zero (0), as the shift to inert anodes in the aluminium smelting process eliminates the need for carbon anodes (see Section **4.2**).

Figure 9. Material flows in 2020 and 2050 under our medium growth scenario




Source: Ramboll, based on data from IAI and European Aluminium.

## 3.4 Determining a carbon budget for European value chain segments

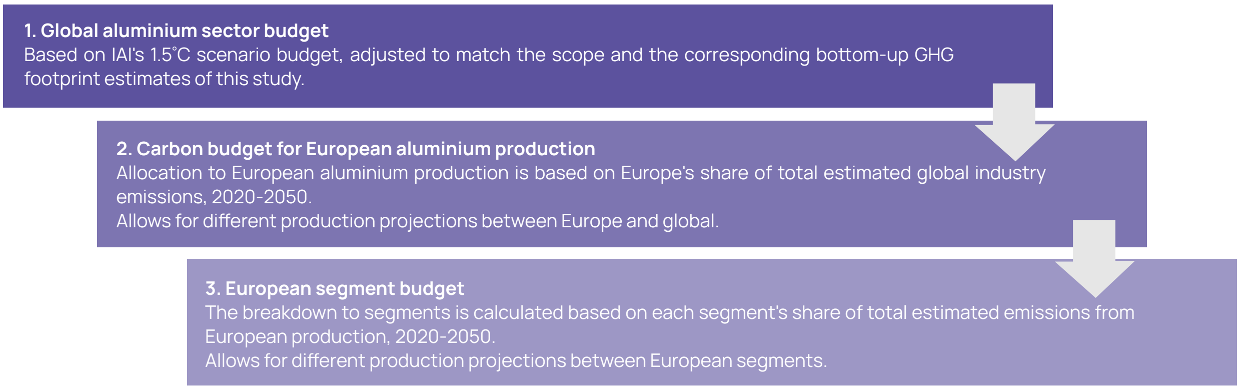
The starting point for defining a carbon budget for the European aluminium industry was the IAI 1.5˚C scenario, which has estimated a carbon budget for the global aluminium industry of 15.9 $GtCO_2e$ between 2020 and 2050[32]. This budget is recognised within the industry and has been used by MPP[33]. However, considering the various methodologies available for defining sectoral carbon budgets and acknowledging the inherent uncertainty surrounding the total amount of GHG emissions that can be emitted to limit global warming to 1.5˚C, we encourage to view the 15.9 $GtCO_2e$ budget as one possible reference point rather than a definitive value. Along these lines, other studies have used different carbon budgets for the global aluminium sector. In a recent study by Eunomia for Zero Waste Europe, for example, a scenario with 66% probability of keeping global warming below 1.5˚C was chosen, rather than a 50% probability that is used in the IAI 1.5˚C scenario. Using this substantially higher probability led in the Eunomia study to a correspondingly much lower total global emissions budget of 9.3 $GtCO_2e$[34]. In this study we followed the IAI's scenario definition.

[32] IAI (2021). 1.5 Degrees Scenario: A Model To Drive Emissions Reduction. Available at: https://international-aluminium.org/resource/1-5-degrees-scenario-a-model-to-drive-emissions-reduction/
[33] MPP (2023). Making Net Zero Aluminium Possible - Technical Appendix. Available at: https://missionpossiblepartnership.org/wp-content/uploads/2023/03/MPP-Aluminium-Technical-Appendix.pdf
[34] Eunomia (2022). Is Net Zero Enough for the Material Production Sector? Available at: https://zerowasteeurope.eu/wp-content/uploads/2022/11/Is-Net-Zero-Enough-for-the-Materials-Sector-Report-1.pdf

Next, the 15.9 $GtCO_2e$ budget was adjusted to align with the scope and the GHG emission estimates used in this study. The global GHG footprint is estimated to about 1,050 Mt $CO_2e$ (see **Table 8**), while the IAI estimates this to be 1,175 $MtCO_2e$[35]. The difference is explained by different scopes of the two values: the IAI includes the foil production segment and GHG emissions from ancillary materials and transport in their estimates, whilst this study does not. When accounting for these differences, IAI's GHG footprint figure falls to an estimated 1,060 $MtCO_2e$ – which brings the error margin of the bottom-up estimates calculated in this study to about 1%.

To ensure equal decarbonisation speed regardless of baseline emissions levels, the global carbon budget of 15.9 $GtCO_2e$ was adjusted by the corresponding ratio between the IAI industry GHG footprint and the one calculated for this study. The resulting global carbon budget was 14.2 $GtCO_2e$.

Figure 10. Approach for allocating carbon budgets to European segments




Source: Ramboll.

Determining carbon budgets for each European segment was then done in a two-step process (**Figure 10**). First, European aluminium production was allocated a specific budget. This was calculated based on the European share of total production over the period 2020-2050. Accounting for expected growth/reductions in European production compared to the global aluminium sector, as is done in this approach, allows for more accurate carbon budgets compared to considering only the current situation. Second, allocation to European segments was done based on each segment's share of estimated European production 2020-2050. As such, different growth forecasts within the European aluminium industry were also considered. The budgets for each European value chain segment are presented in **Table 2**, adding to a total of **344 $MtCO_2e$** in the 2020-2050 period.

Table 2. Carbon budgets for European aluminium production 2020-2050

| | Primary aluminium production | | | | | Semi-fabrication | | Recycling | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bauxite mining | Alumina refining | Smelter | Anode/paste production | Primary cast house | Sheet production | Extrusion | Remelting | Refining | Total |
| Carbon budget 2020-2050 [Mt $CO_2e$] | (n.a.) | 48 | 180 | 9 | 7 | 28 | 16 | 38 | 18 | 344 |

Source: Ramboll.

[35] IAI (2023). Greenhouse Gas Emissions – Aluminium Sector. Available at: https://international-aluminium.org/statistics/greenhouse-gas-emissions-aluminium-sector/

## 3.5 Map current and future decarbonisation options

In order to better understand what decarbonisation technologies may be relevant throughout the aluminium value chain, so-called "decarbonisation clusters" were identified for each segment. The clusters are based on the main types of process activities per segment, and their corresponding energy needs. **Table 3** provides an overview of the decarbonisation clusters mapped to each value chain segment.

Table 3. Decarbonisation clusters for each value chain segment

| Segment | Decarbonisation clusters | | |
|---|---|---|---|
| **Alumina regining** | Digestion | Calcination | Electricity |
| **Smelters** | Anode use | | Electricity |
| **Anode / paste production** | Furnace (high temperature, >600°C) | | Electricity |
| **Cast house (primary)** | Furnace (high temperature, >600°C) | | Electricity |
| **Sheet production** | Furnace (low temperature, <600°C) | | Electricity |
| **Extrusion** | Furnace (low temperature, <600°C) | | Electricity |
| **Recycling (remelting and refining)** | Furnace (high temperature, >600°C) | | Electricity |

Source: Ramboll.

A set of specific emission reduction technologies were then identified for each decarbonisation cluster. While some clusters are specific to just one or a few of the segments, most are recurrent across the aluminium value chain. As such, similar decarbonisation technologies were considered for multiple value chain segments. The conventional production technology and emission reduction technologies considered for each decarbonisation cluster are listed in Table 4.

Table 4. Emission reduction technologies per decarbonisation cluster

| Decarbonisation cluster | Emission reduction technology options[36] |
|---|---|
| **Digestion (steam)** | • Fossil fuels (conventional)<br>• Electric boiler<br>• Hydrogen boiler<br>• Concentrated Solar Thermal (CST)<br>• Mechanical Vapor Recompression (MVR) |
| **Calcination (furnace)** | • Fossil fuels (conventional)<br>• Electrical furnace<br>• Hydrogen furnace<br>• Fossil fuels with Carbon Capture and Storage (CCS) |
| **Electricity** | • Grid-supplied power<br>• Power Purchase Agreement (PPA) / Own generation[37] |
| **Anode use** | • Carbon anode (conventional)<br>• Carbon anode with CCS<br>• Inert anode |
| **Furnace (low temperature, <600°C)** | • Fossil fuels (conventional)<br>• Electrical furnace<br>• Hydrogen furnace<br>• Fossil fuels with CCS |
| **Furnace (high temperature, >600°C)** | • Fossil fuels (conventional)<br>• Electrical furnace<br>• Hydrogen furnace<br>• Fossil fuels with CCS |

Source: Ramboll.

[36] This study only considers technology options that allow full or close to full decarbonisation (in the case of CCS). Thus, technology options leading to partial decarbonisation, for example, furnaces powered by a mix of natural gas and hydrogen are not included in the analysis.
[37] Covers both PPA and plants running on own electricity generation.

To understand the possibility of implementing different decarbonisation technologies, a techno-economic analysis of each option was conducted, considering reduction potential compared to the existing practices (conventional), year of commercial availability, and capital investment costs (CAPEX). This process involved data collection from publicly available sources and industry engagement to validate the findings. The assessment then served as key input for developing decarbonisation pathways. Detailed information on the characteristics of each decarbonisation technology is presented in section **4.2**.

CAPEX estimates for the smelting and alumina refining segments were based on data from MPP[38], except for CST and electric furnaces, where cost estimates were based on data from the US National Renewable Energy Laboratory[39] and Boston Consulting Group[40] respectively. CAPEX cost estimates for alumina refining cover brownfield investments for retrofitting a refinery with new technology for digestion or calcination. For smelters, CAPEX is based on greenfield investments for the technology options. The values for alumina refining and smelting were then converted to cost per tonne of aluminium and corrected to Euro (€) 2022 prices.

Due to limited availability of reliable data for the remaining segments[41], CAPEX values were approximated using CAPEX of the corresponding technology options in the alumina refining calcination cluster and applying the relative share of thermal energy use in each segment and in calcination as calculation factor. While there are clear uncertainties linked to this approach, it was most appropriate considering the lack of publicly available data. CAPEX values for these segments should therefore be considered as best estimates for the purpose of the analysis, rather than empirically determined values.

[38] MPP. (2023). Aluminium decarbonisation at a cost that makes sense.
Available at: https://missionpossiblepartnership.org/wp-content/uploads/2023/04/Aluminum-decarbonization-at-a-cost-that-makes-sense.pdf
[39] National Renewable Energy Laboratory. (n.d.). Concentrating Solar Power. Available at: https://atb.nrel.gov/electricity/2022/concentrating_solar_power
[40] Boston Consulting Group. (2013). Available at: https://www.stahl-online.de/wp-content/uploads/Schlussbericht-Studie-Low-carbon-Europe-2050_-Mai-20131.pdf
[41] Anode production, cast house, sheet production, extrusion, remelting, refining.

## 3.6 Develop a decarbonisation pathway for the European aluminium industry

One of the main objectives of this study was to develop segment-specific decarbonisation pathways for the European aluminium industry, compatible with a 1.5°C future scenario. For this purpose, a decision-making model was developed calculating the cost-optimal strategy for shifting production technologies at a speed necessary to stay below the pre-determined carbon budget, whilst meeting a growing demand for aluminium in Europe.

For each year between 2022 and 2050, the developed model calculates the combination of decarbonisation actions (i.e., technology shifts) that result in the lowest total levelised cost per ton of output product across all value chain segments. The total yearly levelized cost is the sum of the levelised yearly cost of all decarbonization clusters (see section **3.5**). This is calculated considering CAPEX (see **above**), operational expenditures (OPEX) and cost of fuel or electricity for each technology option within each decarbonisation cluster. Calculations, assumptions, and constraints used in the optimisation modelling are presented in **Table 5**.

The model output is i) the annual share of different technology options in each decarbonisation cluster for all segments of the European aluminium industry, ii) emissions reductions per segment and year as well as iii) green energy needs and expected costs of implementing the necessary technology shifts.

Table 5. Key aspects of the developed optimisation model

| Parameter calculations | Assumptions | Constraints |
|---|---|---|
| • **Carbon cost** = EU-ETS forecast until 2050[42]<br>• **OPEX maintenance** = varies as a percentage of CAPEX (between 3-15%) based on expert opinion<br>• **Cost of fuel** = total thermal energy use * levelised cost of fuel [EUR / GJ]<br>• **Cost of electricity** = total electric energy use * levelised cost of electricity [EUR / MWh]<br>• **Total energy use** = Share of thermal energy used per decarbonisation cluster/round-trip efficiency[43]* share of electrified technologies per cluster | • Discount rate = 0%<br>• Cost-optimal decarbonisation, but no constraints on capital investments into decarbonisation technologies in the European aluminium sector<br>• Cash flow of companies/industry is not considered<br>• Companies are willing to write down assets of their entire lifetime (up to 25 years)<br>• PPA/own generation electricity emissions intensity = 10.5 $gCO_2e$/kWh | • Carbon budget for each segment<br>• All segments and decarbonisation clusters must be fully allocated at 100%<br>• Year of commercial availability for each technology<br>• Yearly technology implementation for each technology option follows S-shaped (sigmoidal function) curves, with 10% implementation at first year of commercial availability.<br>• If lowest-emission technologies are chosen and emissions are still above limit, the electricity source can be switched from "Grid" to "PPA / Own generation" |

Source: Ramboll.

## 3.7 Develop an interactive industry decarbonisation monitoring tool

As a final step, an interactive and user-friendly monitoring tool was developed for actors in the European aluminium industry to analyse and regularly assess progress towards company or sectoral milestones. The tool is flexible in design and allows companies to examine their 1.5°C aligned decarbonisation pathway based on company characteristics and individual assumptions, such as segment attribution, electricity mix and Power Purchase Agreements (PPAs)/own generation, production levels, investment costs, year of implementing technology shifts, etc. Other possible customisation options include choosing alternative carbon budgets, the shape of the decarbonisation pathway curve and growth scenarios on production volumes.

[42] Ramboll analysis based on data from the Danish Energy Agency.
[43] Ratio of the useful energy produced by a system to the gross energy consumed to produce this energy.

# 4. Results

# 4. Results

This chapter presents the study results, split into two main sections: the current GHG footprint of the aluminium industry and the 2050 decarbonisation pathway. European aluminium production emitted about 24 $MtCO_2e$ in 2021 (baseline year), with primary production accounting for around 74%, followed by recycling (14%) and semis production (12%). In total, this represents about 2.3% of emissions from the global aluminium industry. When including imports, emissions from the European industry as a share of the total global sector GHG footprint increase to 4.9%.

The 2050 decarbonisation pathway provides a guiding framework for transitioning the European aluminium industry. It shows that emissions reductions of more than 90% can be achieved by following the optimised model pathway. Already by 2030, emissions must decline by more than one-third compared 2021 levels. Decarbonising the electricity grid plays a central role in achieving the pathway, combined with the introduction of inert anodes in smelters and shifts to low-carbon furnaces to abate direct process emissions as well as increased scrap recycling.

## 4.1 The current GHG footprint of the European aluminium industry

The output of primary aluminium and secondary aluminium in Europe is about 3.6 Mt and 11.4 Mt per year[44]. The secondary aluminium amount includes here always run-around material and remelted pre-consumer scrap which are process-related and do not enter the market for secondary aluminium. The primary and remelted aluminium ingots are used as input material for producing semis and for other aluminium products. European semi-fabricators produce 5.2 Mt of sheet and 3.4 Mt extrusion products annually[45]. **Figure 11** shows European production in 2015 and 2021. In general, primary production volumes have decreased slightly over the period, demonstrated by falling smelter and primary cast house volumes.

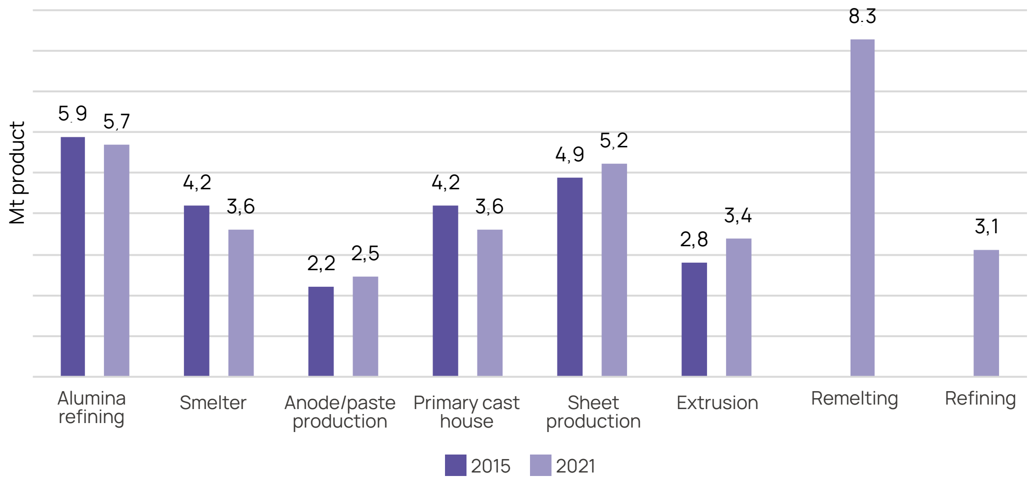
Growing global capacity for primary aluminium production together with high energy prices in Europe over the last couple of years are two reasons that explain this production drop. Meanwhile, European production of semis faces a more positive development, with increasing volumes for both sheet production and extrusion.

The reporting methods for recycling changed between 2015 and 2021. Therefore, no volumes on 2015 production were included for these segments.

> European aluminium production emitted about 24 $MtCO_2e$ in 2021 (baseline year), with primary production accounting for around 74%, followed by recycling (14%) and semis production (12%). In total, this represents about 2.3% of emissions from the global aluminium industry.

[44] Data from European Aluminium. Calculations by Ramboll based on data from European Aluminium for secondary aluminium production.
[45] Data from European Aluminium.

Figure 11. Production volumes in Europe 2015 and 2021[46]




Source: Ramboll based on data from European Aluminium.

Aluminium production is a highly energy intensive industrial process, and a total of 20.3 MWh is required in order to produce a metric tonne of primary aluminium in Europe (**Table 6**). Smelter processes and alumina refining stand out in terms of energy use, demanding, respectively, about 14.5 MWh and 5.0 MWh of energy per tonne of aluminium produced. Primary production also requires far more energy than what is required in both semi-fabrication and secondary aluminium production. Compared to secondary aluminium, the production of primary aluminium requires about 15-20 times the amount of energy.

Table 6. Key figures of European aluminium production

| | Primary aluminium production | | | | | Semi-fabrication | | Recycling | |
|---|---|---|---|---|---|---|---|---|---|
| | Bauxite mining | Alumina refining | Smelter | Anode/paste production | Primary cast house | Sheet production | Extrusion | Remelting | Refining |
| Production in Europe[47] [Mt] | (n.a) | 5.70 | 3.60 | 2.45 | 3.60 | 5.23 | 3.40 | 8.28[48] | 3.10 |
| Total energy intensity[49] [MWh/t Al] | (n.a) | 4.88 | 14.44 | 0.46 | 0.49 | 1.12 | 0.94 | 1.07 | 1.35 |
| Share electric vs thermal energy use [%] | (n.a) | 9 / 91 | 100 / 0 | 21 / 79 | 39 / 61 | 50 / 50 | 56 / 44 | 15 / 85 | 13 / 87 |
| Electric energy use [MWh/t Al] | (n.a) | 0.43 | 14.44 | 0.10 | 0.19 | 0.56 | 0.52 | 0.16 | 0.18 |
| Thermal energy use [GJ/t Al] | (n.a) | 16.03 | 0.00 | 1.32 | 1.07 | 2.03 | 1.51 | 3.27 | 4.24 |
| GHG intensity[50] [$tCO_2e$/t Al] | (n.a) | 1.19 | 3.63 | 0.13 | 0.15 | 0.36 | 0.31 | 0.27 | 0.34 |

Source: Ramboll based on data from European Aluminium.

GHG emissions associated with aluminium production largely follow energy consumption: value chain segments with high energy use also emit the largest share of GHG emissions per tonne of aluminium. In total, primary production in Europe emits 5.1 t $CO_2e$ per tonne of aluminium in Scope 1 and Scope 2, whereas the corresponding value for secondary production is around 0.3 t $CO_2e$ per tonne of aluminium.

[46] Refining figures from EA 2018 data.
[47] Ramboll analysis based on 2021 data from European Aluminium (2018 for refining).
[48] Includes output from extrusion cast houses (3.4 Mt, expert judgement from European Aluminium) and rolling mill cast houses (4.88 Mt, data from European Aluminium). Share of remelting for extrusion is 41% and for sheet 59%).
[49] Ramboll analysis based on data from European Aluminium. Covers energy use in Scope 1 and Scope 2.
[50] Ramboll analysis based on data from European Aluminium. Covers emissions in Scope 1 and Scope 2.

Further, the emission intensity of primary production in Europe is low in relation to those of imports to Europe and global averages (**Table 7**). Energy intensities for imports to Europe and global averages are calculated using global data, and thus do not differ in this study. For GHG emission intensities, global data is used for all segments except for smelters, where different electricity emission factors are applied for imports to Europe vs. global average, respectively (see **Annex**), leading to lower GHG emission intensity for imports at European smelters.

Table 7. Key figures of primary aluminium production outside Europe

| | Primary aluminium production 2021 | | | | | |
|---|---|---|---|---|---|---|
| | Bauxite mining | Alumina refining | Smelter | Anode/paste production | Primary cast house | Total |
| Imports to Europe[51] [Mt Al] | 0.58 | 3.90 | 3.42[52] | | | (n.a) |
| Energy intensity outside Europe[53] [MWh/t Al] | 0.19 | 5.55 | 14.29 | 0.44 | 0.35 | 20.81 |
| GHG intensity imports to Europe[54, 55], [$tCO_2e$/t Al] | 0.06 | 1.81 | 6.21 | 0.12 | 0.11 | 8.32 |
| GHG intensity global[56] [$tCO_2e$/t Al] | 0.06 | 1.81 | 12.95 | 0.12 | 0.11 | 15.06 |

Source: Ramboll based on data from IAI and European Aluminium.

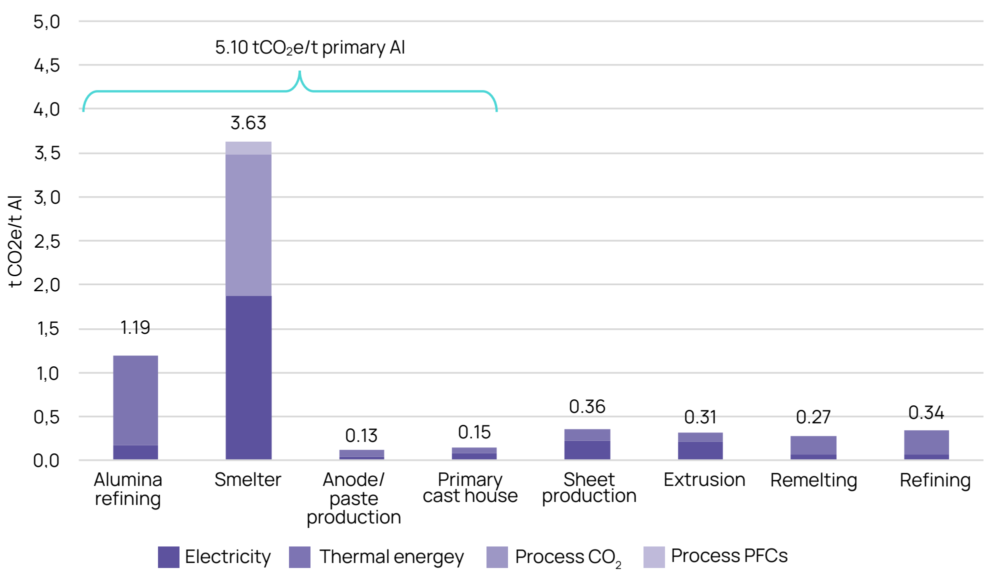
[51] 2021 data. From European Aluminium for alumina and primary aluminium imports, and IAI Alucycle for bauxite imports.
[52] Assumed that primary aluminium imports make up 90% of the total imported aluminium (HS 7601)
[53] Ramboll analysis based on 2019 data from IAI and 2021 data from European Aluminium. Does not include the energy required to produce ancillary materials.
[54] Ramboll analysis based on 2019 data from IAI. Does not include ancillary materials emissions.
[55] Emission intensity for energy used by smelters exporting to Europe based on 2015 data from European Aluminium (mix: 69% hydropower, 22% natural gas, 8% coal, 1% nuclear).
[56] Ramboll analysis based on 2019 data from IAI. Does not include ancillary materials emissions.

The low emissions level of electricity consumption of European primary smelters is driven by extensive use of hydropower and other renewables in the production process (70% share), followed by nuclear (10%), natural gas (9%) and coal and oil (10%)[57]. European primary smelters have also successfully reduced the levels of PFCs emitted in the electrolysis process, which further helps drive down the total GHG intensity. At 0.15 $tCO_2e/t$ Al, PFC emissions from European smelters are only a fifth of the global average of 0.75 $tCO_2e/t$ Al.

The results also suggest a significantly lower emissions profile from European alumina refining (1.19 $tCO_2e/t$ Al) than what is seen globally (1.81 $tCO_2e/t$ Al), compare **Table 6** and **Table 7**. This is explained by a higher share of natural gas and electricity use compared to global average alumina production, that still relies chiefly on coal and oil.

The GHG footprint of producing one tonne of aluminium ingot can be broken down into electricity-related and thermal energy-related emissions, direct process $CO_2$ and PFCs. As seen in **Figure 12**, indirect emissions from electricity use and direction emissions from thermal energy use are the main sources of emissions across the European aluminium value chain segments. For aluminium smelting, the release of direct process $CO_2$, from carbon anode consumption, and PFCs, through the so-called "the anode effect"[58] - account for about 50% of emissions, with electricity use-related emissions representing the other half.

Figure 12. European GHG emissions per tonne of aluminium ingot and type of emissions, for selected value chain segments




Source: Ramboll based on data from European Aluminium.

The current GHG footprint of the European aluminium industry and the total global GHG emissions for each value chain segment are presented in **Table 8**. 24 $MtCO_2e$ are emitted annually from European aluminium production, representing 47% of the total emission from the aluminium industry in Europe, which stands at 51 $MtCO_2e$. The other part, 27 $MtCO_2e$ (53%), is a result of aluminium imports to Europe.

In this study, the GHG footprint of the global aluminium sector for 2021 is estimated to about 1,050 $MtCO_2e$. The lower value compared to IAI's global GHG footprint estimate is explained by different scopes (see Section **3.2**). The lion's share of sector emissions can be attributed to aluminium smelting and alumina refining, both in Europe and globally. Zooming in on European production, **Figure 13** illustrates the shares of the GHG footprint per segment. Together, alumina refining and smelting account for over two-thirds of the total emissions from European production, while secondary production represents 11.0% of the emissions pool. Moreover, European production contributes with 2.3% of global GHG emissions from the industry. When adding imports, European emissions' share of the total global GHG footprint increases to about 4.9%.

[57] 2021 data from European Aluminium.
[58] Anode effect is a phenomenon that occurs when alumina concentration is low in the electrolytic bath and eventually increases the resistance (voltage) in the pot, causing instability and the generation of PFC emissions.

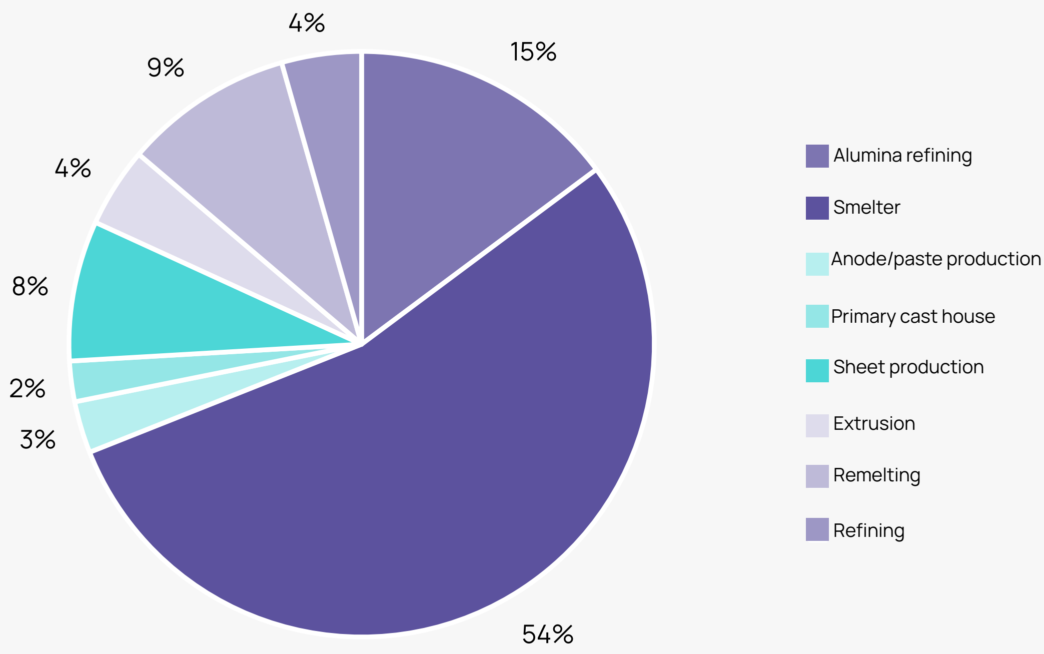
In the next section, the focus is on decarbonising European production. For European imports, the global decarbonisation roadmap developed by the IAI will delineate the necessary emission reduction pathway and corresponding target values for aluminium imports to Europe.

Table 8. GHG footprint of the aluminium sector

| | Primary aluminium production | | | | | Semi-fabrication | | Recycling | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bauxite mining | Alumina refining | Smelter | Anode/paste production | Primary cast house | Sheet production | Extrusion | Remelting | Refining | Total |
| European production [$MtCO_2e$] | (n.a) | 3.57 | 13.06 | 0.69 | 0.54 | 1.87 | 1.06 | 2.26 | 1.06 | 24.11 |
| Imports to Europe[59] [$MtCO_2e$] | 0.18 | 3.71 | 21.23 | 0.93 | 0.38 | 0.39 | 0.15 | | | 27.10 |
| Europe, total [$MtCO^2e$] | 0.18 | 7.28 | 34.30 | 1.63 | 0.92 | 2.26 | 1.21 | 2.32 | 1.12 | 51.22 |
| Global [$MtCO_2e$] | 4.62 | 122.25 | 868.90 | 8.31 | 7.45 | 18.13 | 8.99 | 6.64 | 3.94 | 1,049.22 |

Source: Ramboll based on data from IAI and European Aluminium.

Figure 13. Per-segment shares of GHG emissions from European aluminium production




Source: Ramboll, based on data from European Aluminium.

[59] Import volumes of primary aluminium based on data from European Aluminium. Volumes of semi-fabrication production based on data from Eurostat and cover only EU27. Volumes of secondary aluminium are assumed to be 10% of total imported aluminium (HS 7601) as reported by European Aluminium. Emission intensities of European production is used as proxy to calculate the GHG footprint of these secondary imports.

## 4.2 2050 pathway to decarbonise the European aluminium industry compatible with a 1.5°C scenario

The 2050 decarbonisation pathways have been developed in this study with the intention to provide a guiding framework for transitioning the European aluminium industry to net zero. When considering decarbonisation pathways, one must be mindful of the inherent limitations. There is no one single pathway, and uncertainties still exist e.g., regarding which technologies can be used – and will be preferred – to achieve the necessary emissions reductions. What technologies are implemented will depend on innovation rates and advances for local electricity and hydrogen markets, which in turn are affected by policies and other external events and trends. While technology options for these pathways have been selected based on their application for the sector as a whole, different sets of options might be viable in specific cases and locations. It is also important to note that the results presented in this section are a consequence of the assumptions and the algorithm applied in the optimisation model. Nevertheless, the decarbonisation pathways presented in this study helps identify main levers and milestone for advancing a net zero aluminium industry by 2050.

This section examines the characteristics of different technologies for decarbonising aluminium production in Europe, including emissions reduction potential, expected year of commercialisation, and investment costs. The modelled pathways and key developments between now and 2050 are then presented and discussed. Lastly, the increased needs for low-carbon electricity and green hydrogen that will be necessary to deliver the pathways are described.

### 4.2.1 Technology options for decarbonising European aluminium production

Abating direct (Scope 1) and indirect (Scope 2) process emissions lies at the core of successfully limiting the aluminium sectors' GHG footprint. For indirect emissions, reductions are achieved by switching production power supply away from fossil fuels basis to low-carbon alternatives. While all segments use power supplied from the electricity grid, electricity-related indirect emissions primarily concern smelters due to the electricity-intensive electrolysis process. In Europe, the average carbon-intensity of electric energy used to operate smelters in the region is already comparatively very low. But as shown below, PPAs as instrument to increase deployment of own low-carbon energy generation will be necessary for the smelting segment in order to reach its reduction targets, if current national grid decarbonisation targets are kept as planned and not exceeded.

Direct emissions from aluminium production stem from both the combustion-based thermal energy used in alumina refining to produce steam, and in several other segments to heat and melt aluminium, as well as from the process emissions ($CO_2$ and PFCs) during aluminium smelting. The demand for thermal energy in European aluminium production is currently satisfied by combustion of natural gas. For most segments, shifting to electric or hydrogen-powered furnaces has been identified as the main technology option, together with potentially adding Carbon Capture and Storage (CCS) technology to plants that continue running on natural gas. However, further research and testing must be carried out to better understand if these solutions fit the aluminium production processes. The availability of low-carbon electricity and hydrogen is a prerequisite for electric and hydrogen furnaces to be viable decarbonisation options. The different alternatives to fossil fuel-powered furnaces are expected to become commercially ready after 2030, starting with electric furnaces followed by hydrogen. However, using hydrogen to produce thermal energy results in substantially lower round-trip efficiency[60] than electric furnaces (see **Table 9**), thus the overall applicability of using hydrogen to power furnaces appears less favourable in this exercise.

The shift from natural gas combustion for steam production for digestion (as part of alumina refining) can be realised by deploying electric boilers and hydrogen boilers. As in the case of furnaces, the success of electric and hydrogen boilers depends on the secure supply of low-carbon electricity and/or hydrogen. Also here, the use of hydrogen to produce heat is less suitable compared to electric boilers, due to its low round-trip efficiency ratio. Other possible technology options for generating steam with a lower GHG footprint are Concentrated Solar Thermal (CST) and Mechanical Vapor Recompression (MVR)[61]. According to findings of the MPP project, CST and MVR could reduce emissions from steam production by 75% and 95%, respectively[62]. While MVR can, in principle, be implemented regardless of location, CST is limited to regions where solar exposure is high. In terms of commercial readiness, electric boiler technology is mature, with deployment in European alumina refineries expected from 2025. Hydrogen boilers, CST and MVR are all promising alternatives but require further development before commercial deployment in the context of alumina refining is possible, likely not before 2027 onwards.

[60] Ratio of the useful energy produced by a system to the gross energy consumed to produce this energy.
[61] MVR systems recover and recompress waste process heat, which can then be fed into the process anew. With a round-trip efficiency of 300%, MVR systems help reduce the energy demand from fossil fuels by a factor of three.
[62] MPP (2023). Making Net-Zero Aluminium Possible. Available at: https://missionpossiblepartnership.org/wp-content/uploads/2023/04/Making-1.5-Aligned-Aluminium-possible.pdf

In smelting, process emissions are mainly generated from the consumption of carbon anodes. Emissions savings are achieved either by substituting carbon anodes with inert anodes or by deploying CCS technology to conventional smelters. With an emissions reduction potential of around 95% and costs expected to match conventional smelting, inert anode technology provides a promising avenue for smelter decarbonisation. However, more efforts are needed in order to scale this technology from pilots to commercial use, which is not expected until 2035. Due to the low concentration of $CO_2$ in smelters' flue gases, deploying CCS technology in the sector is less effective, and thereby more costly per tonne of captured $CO_2$, than in other energy intensive production sectors such as cement, steel, and fertiliser production. As CCS technology develops, investments will likely flow into these comparatively more cost-effective sectors first, delaying commercial deployment of CCS in aluminium smelting facilities.

**Table 9** presents an overview of the assessed reduction potential, year of commercial readiness and CAPEX for each technology option considered in this analysis. The results apply at sectoral level and do not necessarily reflect the suitability of certain technology options in local contexts. Hence, options that are not viable for the sector as a whole, may be favourable to implement in specific projects or cases.  The GHG emission intensity of electric and hydrogen boilers and furnaces depends on the emissions intensity of the grid electricity or hydrogen, for which a reduction over time is expected, or on the use of PPAs or own generation, respectively. The method for calculating CAPEX is described in Section **3.5**.

Table 9. Assessment of selected decarbonisation technology options

| Segment | Decarbonisation cluster | Technology | GHG intensity [$tCO_2e/t$ Al][63] | Round-trip efficiency[64] | Year of commercial readiness[65] | CAPEX (2022 prices) [€/t Al][66, 67] |
|---|---|---|---|---|---|---|
| | Primary aluminium production | | | | | |
| **Alumina refining** | Digestion | Fossil fuels (conventional) | 0.68 | n.a. | 2020 | 28.0 |
| | | Electric boiler | Grid or PPA/own generation | 98% | 2025 | 30.7 |
| | | Hydrogen boiler | Grid or PPA/own generation | 25% | 2027 | 28.0 |
| | | Concentrated Solar Thermal (CST) | 0.17 | n.a. | 2027 | 3,550.9 |
| | | Mechanical Vapor Recompression (MVR) | 0.03 | 300% | 2027 | 76.9 |
| | Calcination | Fossil fuels (conventional) | 0.34 | n.a. | 2020 | 18.4 |
| | | Electrical furnace | Grid or PPA/own generation | 95% | 2030 | 155.6 |
| | | Hydrogen furnace | Grid or PPA/own generation | 25% | 2035 | 74.9 |
| | | Fossil fuels + CCS | 0.08 | n.a. | 2030 | 85.1 |
| **Smelter** | Anode use | Carbon anode (conventional) | 1.75 | n.a. | 2020 | 6,309.1 |
| | | Carbon anode + CCS | 0.96 | n.a. | 2035 | 6,688.6 |
| | | Inert anode | 0.08 | n.a. | 2035 | 6,309.1 |
| **Anode /paste production** | Furnace (high temperature, >600 °C) | Fossil fuels (conventional) | 0.09 | n.a. | 2020 | 4.5 |
| | | Electric furnace | Grid or PPA/own generation | 95% | 2030 | 38.3 |
| | | Hydrogen furnace | Grid or PPA/own generation | 25% | 2035 | 18.4 |
| | | Fossil fuels + CCS | 0.02 | n.a. | 2030 | 20.9 |

[63] Ramboll analysis based on data from MPP.
[64] Ratio of the useful energy produced by a system to the gross energy consumed to produce this energy. Ramboll analysis
[65] Ramboll analysis based on data from MPP and industry engagement.
[66] Ramboll analysis based on data from MPP, National Renewable Energy Laboratory (for CST), Boston Consulting Group (for electrical furnaces), and industry engagement. Estimates cover greenfield investments for the smelter segment and retrofitting of existing facilities (brownfield investment) for all other segments.
[67] For all segments except alumina refining and smelters, CAPEX costs are approximated based on relative share of thermal energy use (see also section 3.5). They should therefore be considered estimates for the purpose of the exercise rather than true values.

| Segment | Decarbonisation cluster | Technology | GHG intensity [tCO2e/t Al][63] | Round-trip efficiency[64] | Year of commercial readiness[65] | CAPEX (2022 prices) [€/t Al][66, 67] |
|---|---|---|---|---|---|---|
| **Primary cast house** | Furnace (high temperature, >600˚C) | Fossil fuels (conventional) | 0.07 | n.a. | 2020 | 3.7 |
| | | Electric furnace | Grid or PPA/own generation | 95% | 2030 | 31.3 |
| | | Hydrogen furnace | Grid or PPA/own generation | 25% | 2035 | 15.1 |
| | | Fossil fuels + CCS | 0.02 | n.a. | 2030 | 17.1 |
| **Semi-fabrication** | | | | | | |
| **Sheet production** | Furnace (low temperature, <600˚C) | Fossil fuels (conventional) | 0.13 | n.a. | 2020 | 7.0 |
| | | Electric furnace | Grid or PPA/own generation | 95% | 2030 | 59.0 |
| | | Hydrogen furnace | Grid or PPA/own generation | 25% | 2035 | 28.4 |
| | | Fossil fuels + CCS | 0.03 | n.a. | 2030 | 32.3 |
| **Extrusion** | Furnace (low temperature, <600˚C) | Fossil fuels (conventional) | 0.10 | n.a. | 2020 | 5.2 |
| | | Electric furnace | Grid or PPA/own generation | 95% | 2030 | 43.9 |
| | | Hydrogen furnace | Grid or PPA/own generation | 25% | 2035 | 21.1 |
| | | Fossil fuels + CCS | 0.02 | n.a. | 2030 | 24.0 |
| **Recycling** | | | | | | |
| **Remelting (sheet and extrusion)** | Furnace (high temperature, >600˚C) | Fossil fuels (conventional) | 0.21 | n.a. | 2020 | 11.3 |
| | | Electric furnace | Grid or PPA/own generation | 95% | 2030 | 95.3 |
| | | Hydrogen furnace | Grid or PPA/own generation | 25% | 2035 | 45.9 |
| | | Fossil fuels + CCS | 0.05 | n.a. | 2030 | 52.1 |
| **Refining** | Furnace (high temperature, >600˚C) | Fossil fuels (conventional) | 0.27 | n.a. | 2020 | 14.6 |
| | | Electric furnace | Grid or PPA/own generation | 95% | 2030 | 123.4 |
| | | Hydrogen furnace | Grid or PPA/own generation | 25% | 2035 | 59.4 |
| | | Fossil fuels + CCS | 0.07 | n.a. | 2030 | 67.5 |
| **All segments** | | | | | | |
| | Electricity | Grid | Grid | 100% | 2020 | Grid/PPA |
| | Electricity | PPA / Own generation | PPA / Own generation | 100% | 2020 | Grid/PPA |

Source: Ramboll analysis, based on data from MPP, US National Renewable Energy Laboratory, Boston Consulting Group and industry engagement

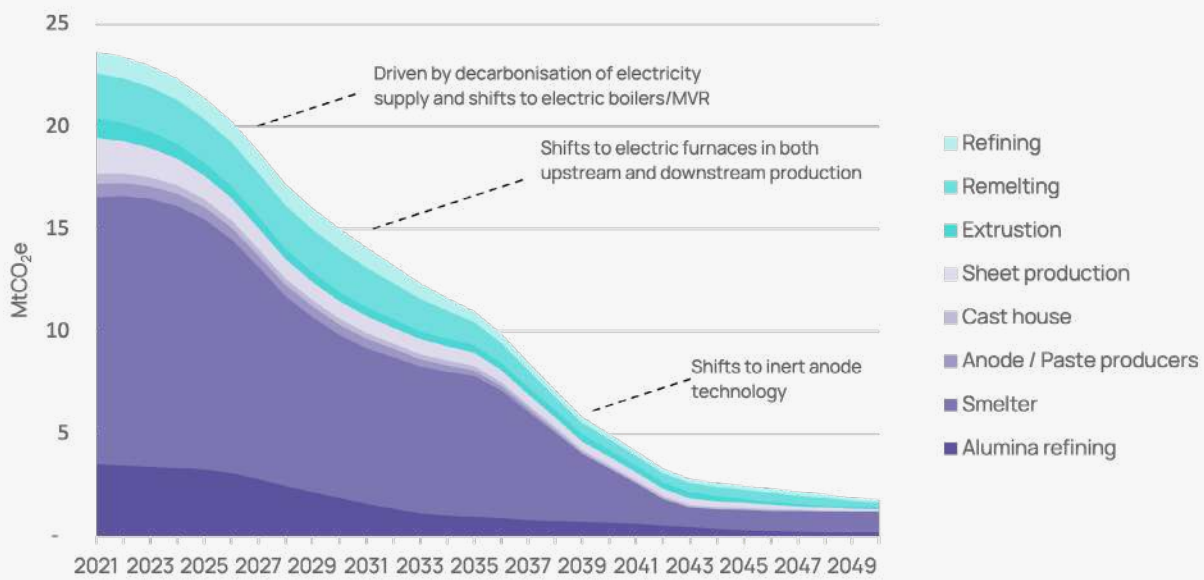
### 4.2.2 Overview of the pathway and key milestones

As illustrated in **Figure 14**, decarbonising European aluminium production in line with a 1.5°C scenario will require substantial GHG emission reductions across the value chain. Starting from 24.1 $MtCO_2e$ of annual emissions in 2021 (see **Table 8**), the main pathway foresees emission levels falling to 1.8 $MtCO_2e$ in 2050. This represents a total emissions reduction of 92.4% for aluminium production in Europe compared to the current baseline. With its substantial contribution to industry GHG emissions, primary aluminium production is given a steeper reduction trajectory with a 93.0% decline between 2021 and 2050, compared to an 88.9% reduction in secondary production. In absolute numbers, aluminium smelters and alumina refining segments achieve the biggest reductions, with their emissions dropping from 13.1 and 3.6 $MtCO_2e$ to 1.0 and 0.2 $MtCO_2e$ respectively (92.2% and 94.5% reduction, respectively).

Further, the pathway shows that significant decarbonisation efforts will need to materialise already by the end of this decade in order to stay within a 1.5°C aligned budget, see **Table 10**. By 2030, GHG emission levels are down to around 15 $MtCO_2e$, representing a 37% decline compared to the 2021 baseline. This is mainly achieved by grid decarbonisation, together with smelters rapidly shifting to PPAs and/or own low-carbon electricity generation to further drive down electricity emissions. Reductions are also found in the alumina refining segment, where new technologies for digestion are introduced starting 2025. From 2030 onwards electric furnaces are deployed across the industry, as alternatives to conventional fossil fuel furnaces. Shifting smelting production to inert anode technology represents the final major effort in decarbonising the industry, which is expected from 2035.

Further reductions in the emissions intensity of electricity consumed in production, mainly through an increased dependency on PPAs/own low-carbon power generation, are then expected in the 2040-2050 period. Indeed, this indicates that the forecasted emissions trajectory for grid-supplied electricity will not be sufficient to decarbonise European aluminium production.

Figure 14. Decarbonisation pathway for European aluminium production




Source: Ramboll analysis.

CCS is not expected to play a role in decarbonising the aluminium industry according to the outlined pathway. This is explained by the lower reduction potential of CCS technology compared to other technology options, and the strong cost-inefficiencies associated with implementing it only as an intermediary solution. An alternative pathway scenario where CCS is implemented as an intermediary reduction technology for the smelting segment is, however, presented in **Box 1. Alternative Scenario Pathway I – CCS deployment in smelters** (below).

Regarding hydrogen furnaces, the technology does not emerge as a solution in the outlined pathway, as designed by the optimisation model. This is due to a high levelised cost of hydrogen energy throughout the entire time period (2021-2050), and hydrogen is therefore considered a cost-inefficient option for achieving necessary emissions reduction. This result applies on sectoral level, though in specific locations and circumstances this technology can be viable and effective. An alternative scenario where hydrogen is deployed in semi-fabrication and recycling segments is presented in **Box 2. Alternative Scenario Pathway II – Hydrogen in semi-fabrication and recycling segments**.

Table 10. Key milestones per decade – GHG emission levels and percentage reductions

| Year | GHG emissions ($MtCO_2e$) | Reduction compared to baseline (2021) |
|---|---|---|
| 2021 | 24.1 | - |
| 2030 | 15.2 | 36.9% |
| 2040 | 5.2 | 78.3% |
| 2050 | 1.8 | 92.4% |

Source: Ramboll analysis.

To achieve the outlined pathway while expanding production to meet growing demand, significant reductions of emission intensities are expected across the entire European value chain. A 93.6% decline in emission intensity is required for smelters, while other segments primary aluminium production, as well as semi-fabrication, must achieve reductions of 95% or over. For secondary production, this level is around 93.5%. Emission intensities for each segment are depicted in **Table 11**.

Table 11. Emission intensities of European aluminium production, 2021 and 2050

| | Primary aluminium production | | | | | Semi-fabrication | | Recycling | |
|---|---|---|---|---|---|---|---|---|---|
| | Bauxite mining | Alumina refining | Smelter | Anode/paste production[68] | Primary cast house | Sheet production | Extrusion | Remelting | Refining |
| 2021 emission intensity [$tCO_2e/t$ Al] | (n.a.) | 1.192 | 3.628 | 0.127 | 0.150 | 0.357 | 0.312 | 0.273 | 0.343 |
| 2050 emission intensity [$tCO_2e/t$ Al] | (n.a.) | 0.059 | 0.232 | n.a. | 0.007 | 0.017 | 0.015 | 0.018 | 0.022 |
| Percentage reduction [%] | (n.a.) | -95.0% | -93.6% | -100% | -95.0% | -95.3% | -95.3% | -93.5% | -93.7% |

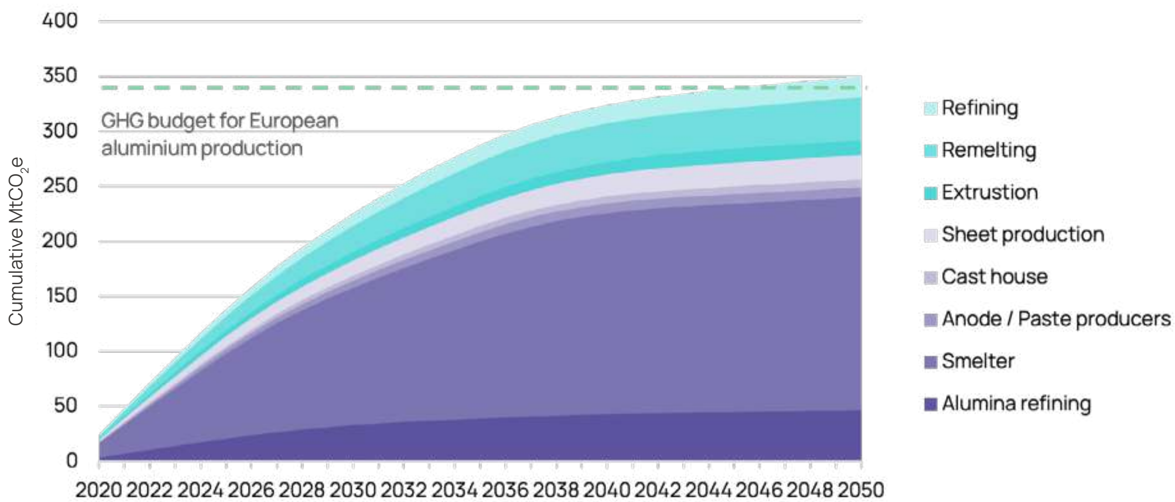
Source: Ramboll analysis.

[68] Since no anode/paste production occurs in 2050, the emission intensity is 0. Anode/paste production ends between 2040-2045 as aluminium smelters shift to inert anodes.

The cumulative GHG emissions between 2020 and 2050 sum up to about 355 $MtCO_2e$ in 2050 (see **Figure 15**). The shape of the curve is as can be expected, since cumulative emission increase rapidly while GHG emission levels are high and stabilise as the sector shift to low-carbon production technologies. Of the total cumulative emissions from European production, smelters account for more than half (55%, 194 $MtCO_2e$), followed by alumina refining representing about 13% (46 $MtCO_2e$) and remelting another 11% (39 $MtCO_2e$).

The total cumulative emissions end up slightly above the 1.5°C-aligned GHG budget of 345 $MtCO_2e$ attributed to European production (see Section 3.4), overshooting by 3.3%. This is due to the smelting segment, which overshoots its budget of 180 $MtCO_2e$ by 8%, proving that rapid decarbonisation of smelters is challenging even with ambitious assumptions on low-carbon electricity supply and inert anode deployment being in place. However, as seen in **Table 11**, by 2050, all segments achieve considerable reductions in emissions intensities. Hence, by decarbonising production in line with the outlined pathway, with its underlying assumptions and constraints, the European aluminium industry can play their part in reaching Europe's overall climate targets.

Figure 15. Cumulative GHG Emissions from European aluminium production until 2050




Source: Ramboll analysis.

### 4.2.3 Segment-specific pathways

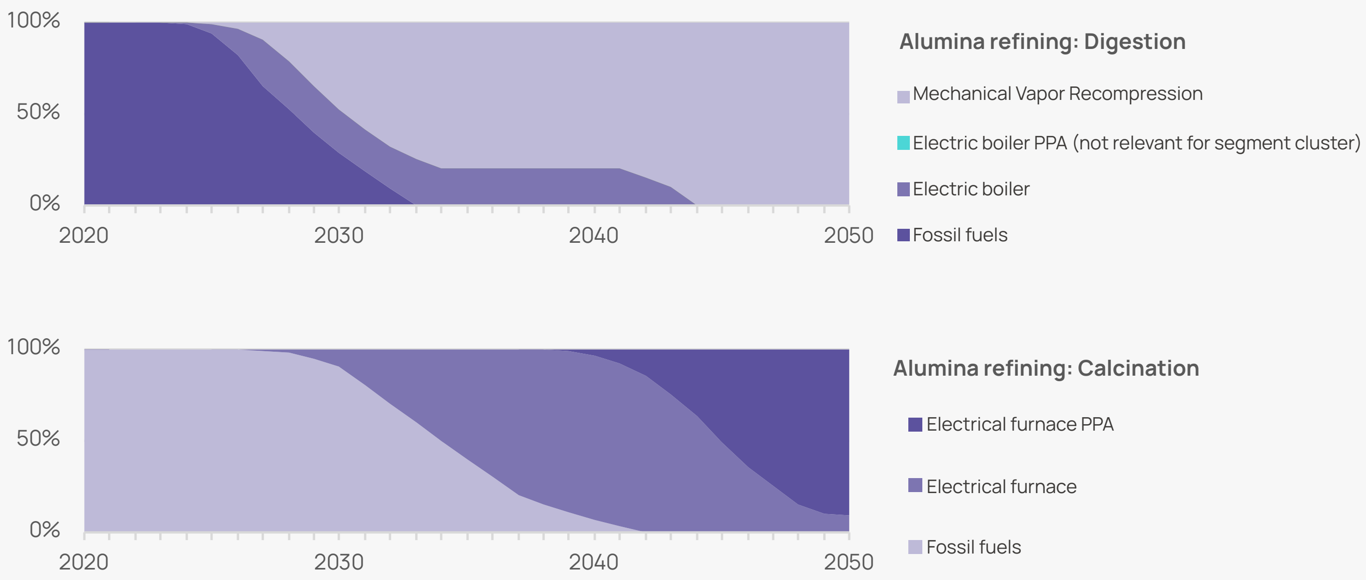
The pathway of decarbonisation will vary for the different segments, depending on current emissions profiles, their share of thermal and electric energy, and available technology options. This section describes main characteristics and key milestones for each value chain segment.

#### Alumina refining

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 then introduced from 2025 to advance emissions savings, together with MVR technology that becomes a viable option closer to 2030. MVR continues to grow in importance and is deployed for all digestion processes closer to 2045.

For calcination, electric furnaces are implemented from 2030 onwards in order to mitigate emissions from fossil fuel power furnaces, and reaches full market penetration by 2040. However, this coincides with a growing need for PPAs or own energy generation in order to supply the electric furnaces with low-carbon electricity, and it indicates that relying on the grid for electricity supply will not be enough to deliver the full emission reductions imposed on the segment.

Figure 16. Alumina refining decarbonisation technology path

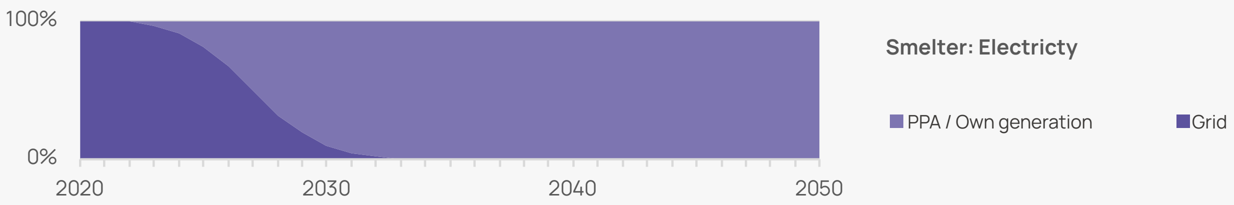



Source: Ramboll analysis.

## Smelters

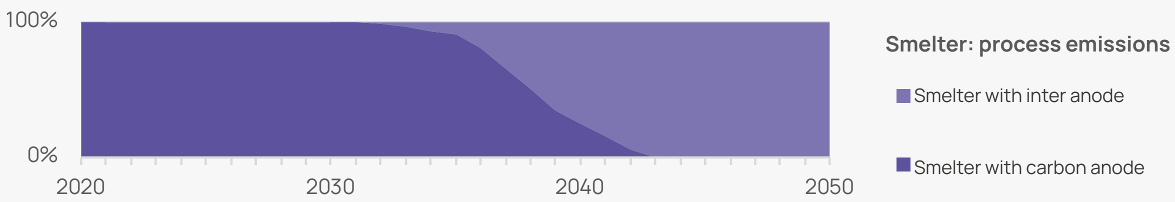
Between today and 2035, emission savings from smelting processes are driven in part by improved emission-intensities from grid-supplied electricity. The forecasted general developments of the grid will, however, not be sufficient to deliver smelter decarbonisation in line with the 1.5℃ pathways. Shifting smelter power supply to low-carbon PPAs or own generation are therefore assessed to be necessary, beginning around 2025 and being fully implemented about a decade later, see Figure 17. Inert anodes become available by 2035 and are implemented over the next ten years (Figure 18). By 2045, smelters have fully shifted from carbon anode to inert anode in order to address process emissions. Further GHG emissions reductions in the smelter segment during this period follow the decarbonisation of the electricity grid, combined with a continued use of PPAs and/or own generation to ensure supply of green electricity. The main pathway in this modelling exercise foresees no deployment of CCS, but an alternative scenario that where CCS is introduced as an intermediary solution is presented in Box 1 (**below**).

Figure 17. Smelter electricity pathway




Source: Ramboll analysis.

Figure 18. Smelter decarbonisation technology path

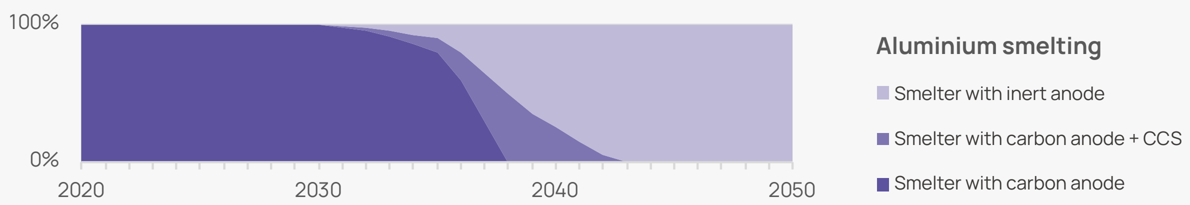



Source: Ramboll analysis.

## Box 1. Alternative Scenario Pathway I – CCS deployment in smelters

In this alternative scenario, CCS technology is rolled-out as an intermediary reduction measure alongside the deployment of inert anodes. Because the emissions reductions achieved by CCS technology in smelters (assumed to be 45%, see Section 4.2.1.) would still not reach necessary reduction levels in 2050, all European smelters will need to operate using inert anodes by then. The speed of inert anode deployment remains the same as in the main scenario, reaching full market coverage by 2043. As such, GHG emissions from carbon anode use are mitigated at a steeper rate by implementing CCS technology, but the emissions intensity in 2050 is unchanged.

Smelter decarbonisation pathway including CCS technology




Source: Ramboll analysis.

Deploying CCS technology in the smelting process reduces GHG emissions by 6.6 $MtCO_2e$ between 2021-2050, or 3.4%, compared to the optimised pathway scenario. In relation to the overall budget for European aluminum production, this corresponds to a 1.9% reduction and results in overshooting by 1.4% instead of 3.3%. When considering only direct process emissions, the introduction of CCS according to the above pathway contributes to a 5.2% emissions decline.

Difference in GHG emissions between main and alternative scenario

| | Smelter direct process | Smelter total | European production total |
|---|---|---|---|
| Cumulative GHG emissions optimised scenario [$MtCO_2e$] | 128.3 | 194.1 | 354.6 |
| Cumulative GHG emissions CCS scenario [$MtCO_2e$] | 121.7 | 187.5 | 348.0 |
| Absolute reduction [$MtCO_2e$] | -6.6 | -6.6 | -6.6 |
| Percentage reduction [%] | -5.2% | -3.4% | -1.9% |

Source: Ramboll analysis.

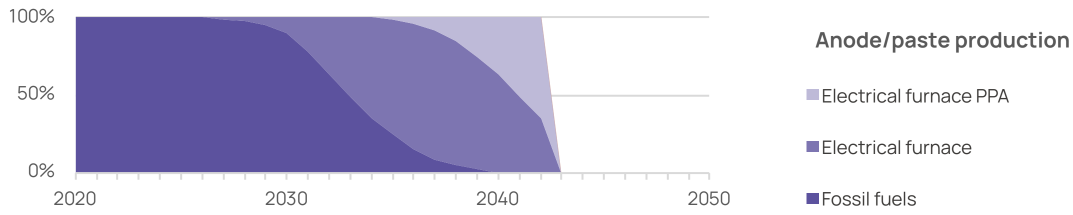
Although encouraging from an emissions reduction perspective, the feasibility of this scenario is limited by low investment incentives, both relating to timing and costs. First, the lifetime of CCS facilities in this scenario is limited to only about ten years before being phased out and substituted by inert anodes, while the technical lifetime for CCS projects on natural gas-powered furnaces are around 25 years. The rapid substitution provides the fastest route to emissions reduction, but will heavily impair any decisions to invest in CCS facilities decisions.

Second, introducing CCS technology results in a near 50% surge of estimated total CAPEX costs in the smelting segment compared to the optimised scenario with no CCS deployment. This indicates potentially lower cost-effectiveness of relying on CCS as a bridge solution, and the benefit of reducing total emissions from aluminium production by 1.9% over the 2021-2050 period should be considered against the alternative of instead directing capital investments into R&D and implementation of technologies able to support full sector decarbonisation.

## Anode/paste production

The anode/paste production segment decarbonises through electric furnaces, with commercial deployment expected to begin in 2030. From 2035, PPAs or installation of own low-carbon power generation for running the electric furnaces will be required to meet pathway targets. With the introduction of inert anodes in the smelting process, conventional carbon anodes will no longer be required in primary aluminium production. As inert anodes reach full market coverage, expected to occur between 2040 and 2045, the production of anode/paste will be entirely phased out.

Figure 19. Anode/paste production decarbonisation technology path

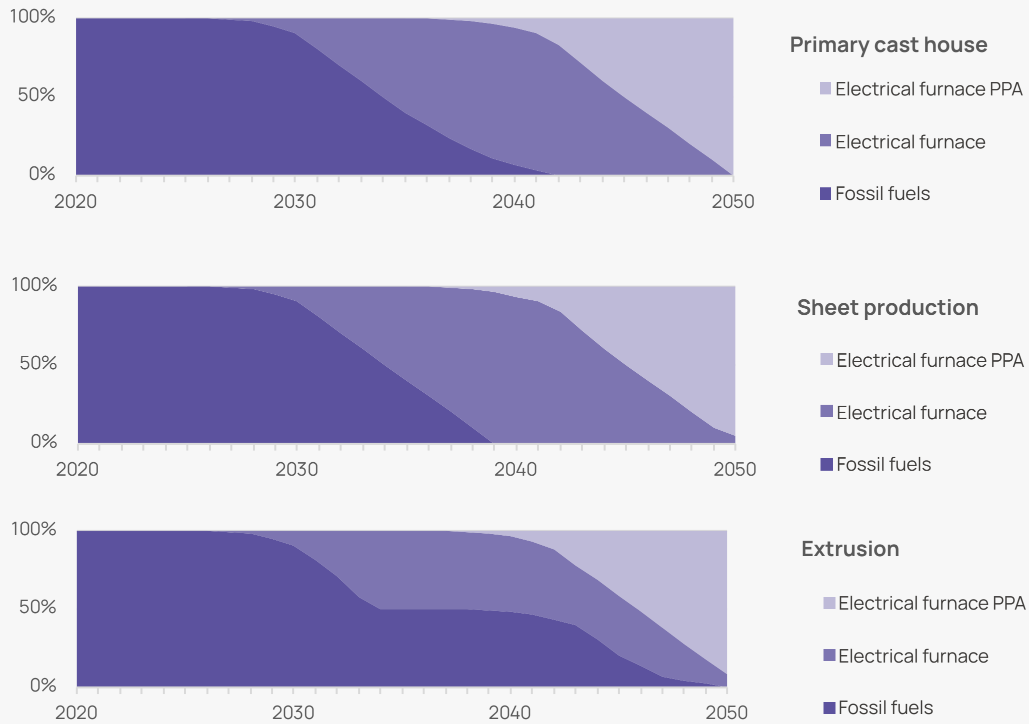


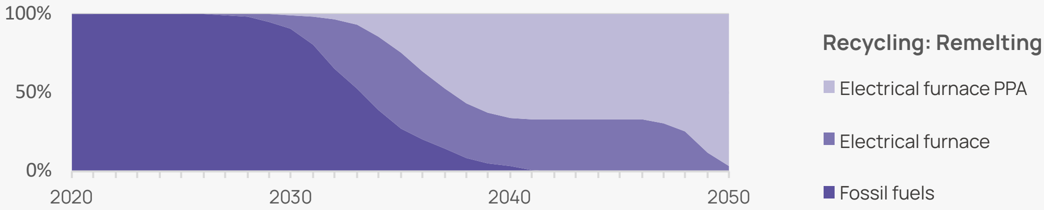

Source: Ramboll analysis.

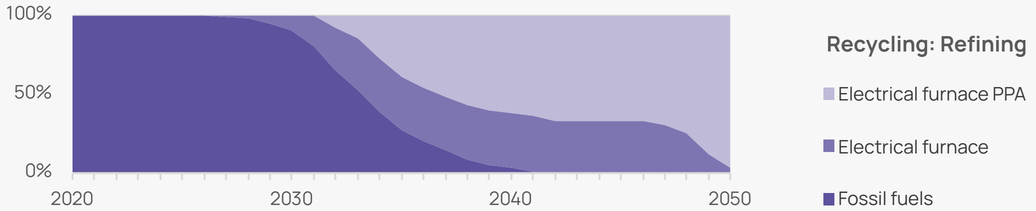
## General segment pathway

For the remaining segments, which all use furnaces to heat or melt aluminium to different temperatures before further treatment, the pathways follow a similar pattern (see **Figure 20**). Between 2020-2030, reductions are driven by improved emissions performance of grid-supplied electricity. In 2030, electric furnaces are introduced across all segments, with recycling segments requiring certain support from PPA/own generation to supply low-carbon electricity supply early on. By 2040, electric furnaces reach full market coverage. Starting by 2040, PPAs or own generation of electricity powering electric furnaces also play a role for delivering emissions reductions in primary cast house and semi-fabrication segments.

Figure 20. General segment decarbonisation technology path





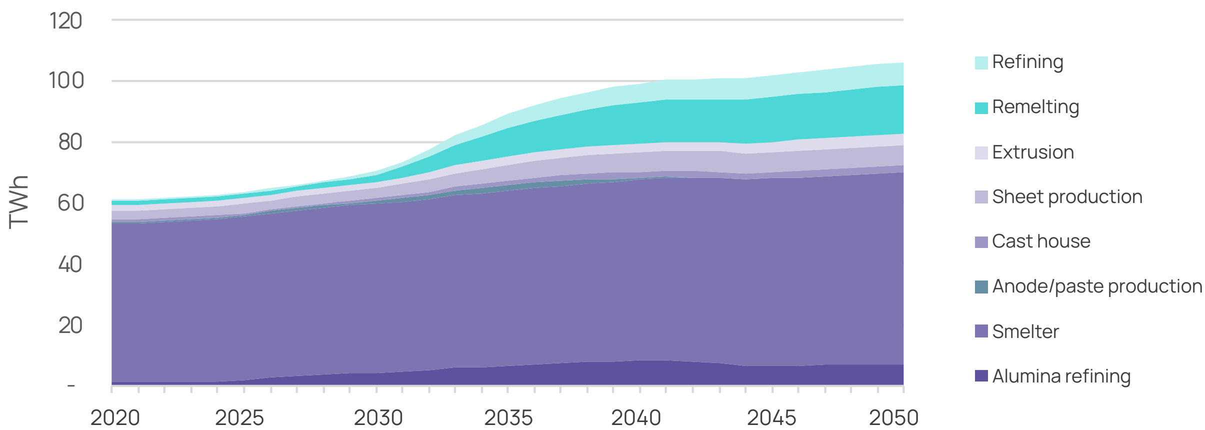




Source: Ramboll analysis.

### 4.2.4 Energy needs linked to the pathway

Decarbonising European aluminium production in line with the proposed pathways, shifting away from fossil fuels to mainly electric-powered technologies, will profoundly increase the sector's demand for low-carbon and reliable electricity supply. Electricity demand per segment between 2022 and 2050 is depicted in **Figure 21**. Unsurprisingly, smelters will need by far the most electricity, but the share will decline as other segments decarbonise through deployment of electric furnaces. In 2020, smelters cover 85% of total electricity demand, in 2050 this share is down to 57%. On aggregate, the demand for electricity almost doubles, increasing by more than 80%% from around 60 Terawatt-hours (TWh) to 110 TWh, i.e. an increase of 50 TWh in electricity demand between 2020 and 2050. This highlights the strong emphasis on increasing low-carbon electricity generation capacity that is pivotal within the aluminium sector, and for Europe as a whole.

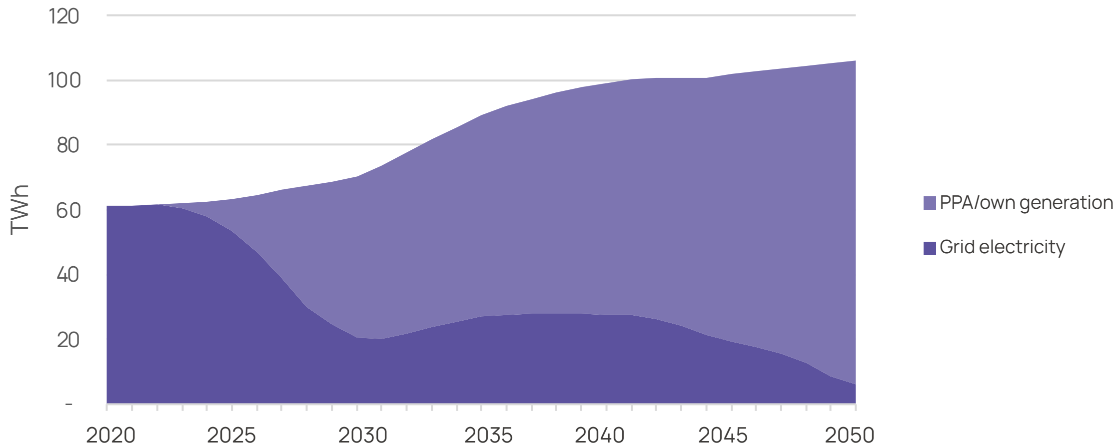
Figure 21. Energy demand per value chain segment




Source: Ramboll.

Further, as the previous sections have shown, only relying on grid decarbonisation will not at all be sufficient to stay on track towards decarbonisation, and already by 2030, a large share of the total electricity use must be supplied by PPA or own generation. The required share of grid electricity and PPA/own generation is illustrated in **Figure 22**.

Figure 22. Development of electricity demand - grid vs PPA/own generation




Source: Ramboll

### 4.2.5 Cost of decarbonisation

Decarbonising the European aluminium industry will require considerable investments into a wide range of areas, including R&D and implementation of new process technologies, clean and reliable energy supplies (e.g., increased renewable generation, upgrading grid network and connections, and advancing storage technology), and improvements of collection schemes and recycling systems for higher material efficiency. In this analysis, we focus on the costs associated with introducing new production technologies within, typically, an existing plant or facility, that is CAPEX costs[69], as this is under direct control of aluminium industry actors. The cost estimates are high-level and subject to immanent uncertainties, and they do not include neither R&D needed to develop and test new technologies, nor the energy systems developments needed to support such technology shifts.[70] As such, the full cost of decarbonising European aluminium production is likely substantially higher.

The underlying model represents the most capital-efficient 1.5°C aligned pathways to stay near the carbon budget attributed to European production and to reach a sustainable emissions rate by mid-decade. Between 2021 and 2050, this will require estimated approximately €33 billion of investments into new technology deployment. About 67% of these estimated costs, ca. €22 billion, are expected to occur in the 2031-40 period. The high costs in this decade are mainly due to expectable investments into greenfield smelter facilities equipped with inert anode technology. In general, the estimates show that smelters face by far the biggest investments costs until 2050. This is because CAPEX cost estimates for smelters are based on greenfield investments, while for all other segments estimates cover brownfield investments, as greenfield costs are currently not available (see Section 3.5 for more information on the methodology for estimating CAPEX). In this sense, future investment costs for downstream segments will be considerably greater.

In a context of future increase in demand, the investment expenses required to substantially expand the capacity for recycling and semi-fabrication will indeed be substantial. While the primary aluminium capacity is expected to remain relatively unchanged, the other segments will undergo significant growth. For future studies, it will be therefore crucial to account for the complete greenfield costs for downstream segments, besides considering the costs associated with decarbonisation. This approach will provide a comprehensive view of the overall investment outlay needed to both increase capacity and implement decarbonisation measures. This figure will be significantly larger than the sole brownfield cost of decarbonisation.

This exercise is a first attempt to calculate the investment needed to decarbonize the European aluminium sector in accordance with a 1.5°C-aligned trajectory. However, it is crucial to underline the substantial uncertainty surrounding the generated figures. This uncertainty stems from both the absence of comprehensive CAPEX and OPEX data for low-carbon technologies across various segments, notably in the downstream sectors, and the high level of unpredictability tied to forthcoming policy and technological advancements. It is therefore advised to conduct a more comprehensive study dedicated to estimating the investment costs across each segment of the aluminium value chain.

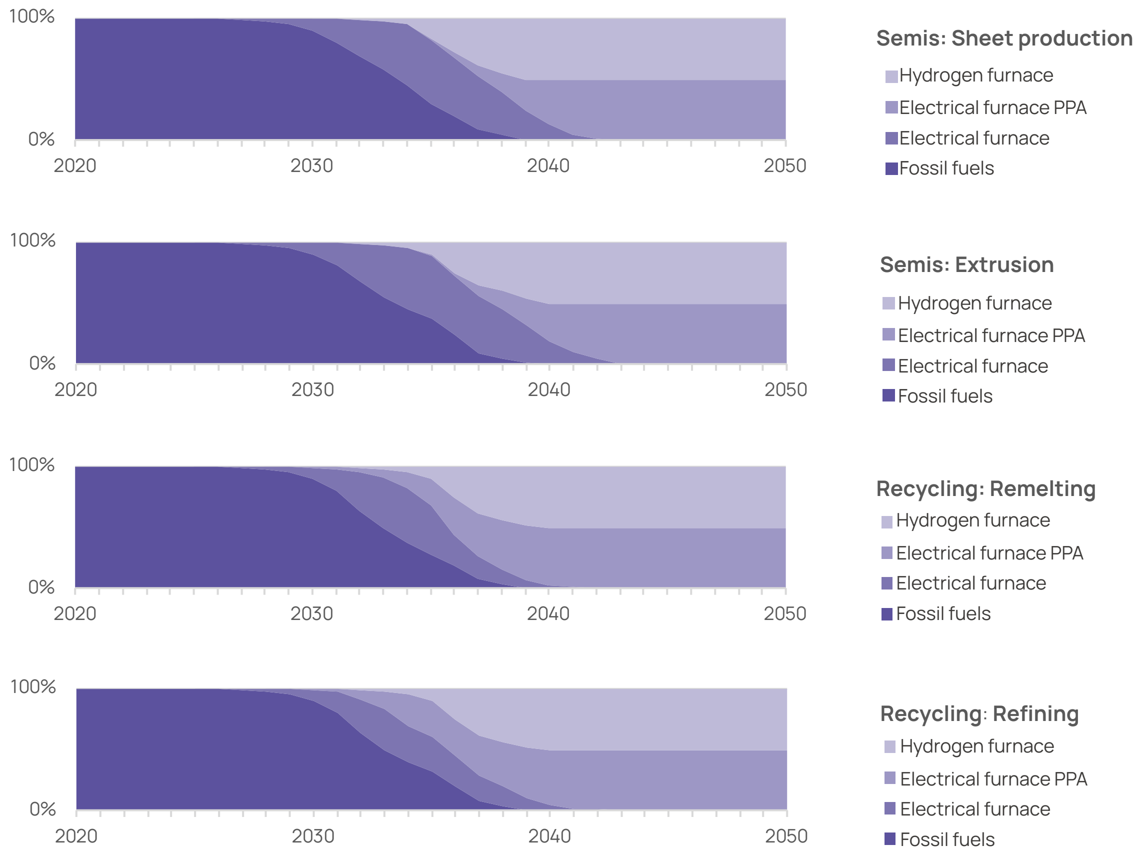
[69] Assuming greenfield investments for aluminium smelting segment and brownfield investments for all other segments.
[70] The uptake of low-carbon technologies, and specifically the increasing electrification of production processes, will be interdependent with the progressive grid decarbonisation.

## Box 2. Alternative Scenario Pathway II – Hydrogen in semi-fabrication and recycling segments

This scenario includes the deployment of green hydrogen, i.e., produced by electrolysis based on 100% renewable electricity, alongside electric furnaces. While the optimisation model suggests widespread deployment of electric furnaces to decarbonise thermal energy use in the aluminium production value chain, much uncertainty still exists regarding which technology options will be implemented across the industry. Several initiatives and ongoing R&D projects are specifically focusing on replacing natural gas with hydrogen, highlighting the industry's interest in such solutions. Shifting to hydrogen requires more limited facility upgrades compared to electric furnace technology. Consequently, such efforts can be less demanding and less capital-intensive to implement.

In this alternative $H_2$-scenario, hydrogen is introduced in downstream and recycling segments starting from 2035. Rapid deployment is expected, with hydrogen supplying about 50% of segments' thermal energy needs by 2040 (electric furnaces covering the other half). As seen in the below figures, hydrogen is implemented alongside electric furnaces mainly relying on PPA and/or own generation for its electricity supply. This is in line with the main pathway developed in the optimisation model.

Semi-fabrication and recycling segments decarbonisation pathway including hydrogen




Source: Ramboll analysis.

## Box 2 – continuation

Introducing hydrogen in semi-fabrication and recycling segments increases total emissions from these segments by around 29 $MtCO_2e$ between 2021-2050, compared to the optimisation model pathway, as seen in the table below. Considering the overall budget, this scenario leads to an overshoot of 11.8% instead of 3.3%. This is due to the relatively high emission intensity for green hydrogen, estimated to be 68.0 $gCO_2e/kWh$[1], while the emission intensity for electricity supplied to electric furnaces with PPA or own electricity generation is assumed to be 10.4 $gCO_2e/kWh$ (average of emission intensities for electricity generated from wind and hydropower).

Difference in GHG emissions between optimised and hydrogen scenario

| | Semi -fabrication | | Recycling | | Total semi-fabrication and recycling |
|---|---|---|---|---|---|
| | Sheet production | Extrusion | Remelting | Refining | |
| Cumulative GHG emissions optimised scenario [$MtCO_2e$] | 25.6 | 15.3 | 39.0 | 18.5 | 98.3 |
| Cumulative GHG emissions H2 scenario [$MtCO_2e$] | 30.7 | 16.3 | 54.5 | 26.1 | 127.5 |
| Absolute change [$MtCO_2e$] | 5.1 | 1.0 | 15.5 | 7.6 | 29.2 |
| Percentage change [%] | 29.9% | 6.4% | 39.8% | 41.2% | 29.7% |

Source: Ramboll analysis.

Still, hydrogen furnaces provide a strong alternative route to decarbonising the European aluminium industry. Compared to natural gas, which is currently the main thermal energy source for European production, green hydrogen-powered furnaces reduce emissions by more than 85%. Further, hydrogen will likely be an important alternative for facilities located in areas with limited access to low-carbon electricity from the grid.

In terms of costs, CAPEX is estimated to decline by around 20% for all segments under consideration in this scenario. OPEX costs are, however, significantly higher when powering furnaces with green hydrogen rather than with low-carbon electricity. In the energy-intense aluminium industry, ensuring cost-competitiveness will be crucial for green hydrogen solutions to become feasible commercial alternatives.

[1] This value represents the full life cycle of green hydrogen, including GHG emissions for renewable energy production, the electrolyser facility as well as transport and storage infrastructure. The 68.0 $gCO_2e/kWh$ value is estimated as double the figure for electricity generation from solar PVs.

# 5. Policy **Recommendations**

# 5. Policy **Recommendations**

Based on the evidence collected, analysis presented, and conclusions drawn, this chapter presents policy recommendations to enable a successful decarbonisation of the European aluminium sector in line with a 1.5°C pathway. Specifically, the recommendations aim to highlight enabling conditions (e.g., policies, investments, etc.) and suggest actions for policy makers and industry operators within four key areas: accelerating the decarbonisation of power generation, prioritising investments in R&D for low-carbon technologies, increasing scrap recovery and recycling, and supporting the European low-carbon and circular production capacity.

The decarbonisation of industries has emerged as a pressing global imperative, and the European aluminium sector stands at the forefront of this transition. Aluminium will play a pivotal role in achieving the targets of the Paris Agreement but remaining within the 1.5°C allocated GHG budget until 2050 will pose significant challenges to the operators in the sector. Addressing these challenges will require decisive actions not only from the industry, but also bold and forward-looking leadership from policymakers, in order to ensure that the necessary enabling conditions are timely and completely in place for the decarbonisation pathways to deliver.

The analysis presented in this study showcases that decarbonising to remain within the 1.5°C carbon budget allocated to the EU aluminium industry, in a context of increasing demand of aluminium products, will require to meet ambitious emission reduction targets. However, without well-planned and targeted policy interventions and/or more favourable conditions, the results from the modelling exercise show that the sector will not be able to remain within its carbon budget. Despite a projected 92.5% reduction in total emissions from the aluminium production in Europe compared to the current baseline, an overshoot of the budget by about 3% is still expected. Nevertheless, by 2050, all segments in the aluminium industry are expected to generate very low GHG emissions.

To support the sector in its decarbonisation efforts, it therefore becomes paramount to identify adequate levers to accelerate the transition and better align the industrial pathway to the 1.5°C degree target of the Paris Agreement.

This necessitates robust policy support in four key action areas:

1. Accelerate the **decarbonisation of power generation at a competitive price**
2. Prioritise and increase **investments in R&D for low-carbon technologies**
3. Increase **scrap recovery and recycling**
4. Incentivise and **support European low-carbon and circular production capacity**.

> Aluminium will play a pivotal role in achieving the targets of the Paris Agreement but **remaining within the 1.5°C allocated GHG budget until 2050 will pose significant challenges to the operators in the sector.**

In addition to supporting the decarbonisation of the European aluminium industry, the presented recommendations serve to simultaneously balance and support the EU's objectives towards the creation of a Circular Economy, improved strategic autonomy, and establishing a fully decarbonised energy system.

An important caveat to highlight is that the findings presented in this study are the result of a specific algorithm, set of assumptions, and type of model used to develop the decarbonisation pathway (specifically, a cost optimisation model). The results obtained apply at the level of the whole sector, but clearly, this does not preclude the possibility that some options which may not look viable for the sector, could be well applied for specific segments, facilities, and locations.

With the right set of support measures put in place to facilitate a rapid deployment and scale up of low-carbon technologies, these options would then become effective for the model at the whole sectoral level, and emissions reductions would also come at an earlier time than currently projected.

## 5.1 Accelerate the decarbonisation of power generation at a competitive price

Since more than 60% of the GHG footprint of primary aluminium is due to the indirect emissions from electricity consumption[71], **cost-competitive low-carbon electricity is the most promising opportunity** in the short to medium term to significantly reduce the emission profile of the European aluminium industry. This study indicates that **PPAs and/or a shift to own decarbonised power generation** will be essential to deliver on the pathway, as relying solely on the decarbonisation of the grid will not be sufficient.

However, primary aluminium production and other heavy industries cannot match the price for PPAs paid by companies in sectors with relatively low energy consumption and without a baseload consumption profile, such as consumer goods and services. Earmarked support to increase the share of aluminium production from low-carbon electricity should therefore be a top priority for policymakers[72]. Yet, several challenges are limiting the possibilities for rapid action.

Although the EU has established ambitious targets for increasing the penetration of renewables in the power generation mix, the progress in deploying and connecting clean energy sources to the grid has varied significantly among EU Member States, with the outcome that aluminium industries often lack access or face competition with other heavy industries for access to renewable grid power.

The varying pace of renewable energy penetration across EU Member States can be attributed to several factors, including different sets of policy frameworks and incentives, market conditions, as well as resource availability and potential. By **enhancing and harmonising the policy frameworks across Member States** to provide a consistent and supportive environment, as well as by **simplifying the permitting process for renewable energy development or setting up Member State/European Investment Bank financial guarantees for long-term PPAs**, it is possible to accelerate the transition to a fully decarbonised power sector. Nevertheless, the current pace of progress on grid decarbonisation, especially in Southern and Eastern Europe, does not allow aluminium companies to rely on renewable electricity from the grid as their primary source of green energy. Especially in countries where baseload decarbonised electricity is not available, aluminium primary producers need mechanisms to deal with significant shaping/firming costs, caused by the intermittent nature of renewable generation. One example of an effective solution is the "Green Pool" concept[73], where an aggregator "pools" together the renewable electricity produced, undertaking all shaping risks and supplying the consumer with baseload power.

[71] IAI (2021). Statistics on Greenhouse Gas Emission Intensity Primary Aluminium. Available at: https://international-aluminium.org/statistics/greenhouse-gas-emissions-intensity-primary-aluminium/
[72] IEA (2022). Aluminium Tracking report. Available at: https://www.iea.org/reports/aluminium
[73] Please find the detailed green pool proposal by ENERVIS, March 2021, here: https://enervis.de/wp-content/uploads/2021/04/enervis_MYTILINEOS_Green-Pool_Final_Report_study_03_2021.pdf


**Expanding access to renewable power in aluminium manufacturing**[74] should therefore become paramount, however it will require the integration of alternative renewable sources including solar photovoltaic (PV), onshore and offshore wind. Indeed, a more rapid deployment of renewables such as solar and wind is crucial considering that conventional hydro and geothermal power, which historically have been providing constant and renewable electricity to smelters, have very limited growth potential and are strongly dependent on location-specific geological features. Therefore, besides promoting schemes like the "Green Pool", the transition to intermittent renewable sources should also include policies promoting the **implementation of energy storage solutions** and supporting developments in **stand-by operations of flexible power plants**, to ensure that smelters have access to reliable green power.

Lastly, it is worthy of note that European consumers who sign a PPA for renewables will still face carbon costs, due to the marginal pricing in the European electricity markets. This is not the case for their competitors in other world regions. Therefore the indirect costs compensation mechanisms should be kept and harmonised, to ensure the global competitiveness of the European electro-intensive industries.

## 5.2 Prioritise and increase investments in R&D for low-carbon technologies

**Boosting investments in Research & Development (R&D)**, thus supporting the implementation of low-carbon technologies is crucial for effectively abating direct process emissions. The groundwork for these technologies must be established as soon as possible, to ensure readiness for the upcoming investment cycle.

Direct process emissions in primary aluminium production stem from two sources: the electrolysis of alumina utilising a carbon anode during smelting, and the combustion of fossil fuels in unit processes to generate heat. Therefore, the highest emission reductions can be achieved with the **deployment of a non-carbon anode** and with the progressive phase-out of fossil fuels in favour of **renewable fuels to provide heat**, and a complement pathway to the **electrification** of processes.

Besides supporting solutions to decarbonise the electrolysis of alumina, the decarbonisation of high temperature thermal heat systems for **steam and calcination** also needs targeted policy support. Alumina refining is the segment with the second highest $CO_2$ emission impact in the aluminium value chain, while **electric calcination** is still in the trial phase. In Australia, a large-scale pilot project is investigating the technical and commercial feasibility of introducing electric calciners in the alumina refining process[75].

While electrification could become one of the leading solutions to decarbonise processes, this analysis also confirms that uncertainty remains on its technical feasibility across segments, as well as on its associated investment costs compared to alternative options, notably green **hydrogen**.

[74] Being large electricity consumers, aluminium producers could provide demand response services to electricity grids with increasing penetration of renewables in the mix.
[75] Australian Renewable Energy Agency. (2022). World-first pilot to electrify calcination in alumina refining.
Available at: https://arena.gov.au/news/world-first-pilot-to-electrify-calcination-in-alumina-refining/

Hydrogen is expected to play a key role in transforming mobility and industry sectors in Europe, with the EU currently attracting more investment in hydrogen energy development than both the United States and China combined[76]. Currently, the use of hydrogen as a substitute for natural gas in furnaces, for example in remelting and refining, is also being explored in the aluminium industry.

Notwithstanding the promising policy environment for hydrogen in the EU, it is currently challenging to predict which technology will have the most prominent role in providing renewable heat to the sector. While hydrogen furnaces might represent an easier technology to implement compared to electric furnaces, the high costs associated with the production of green hydrogen, which can significantly differ across Member States, still limit the economic viability of this fuel. Concerns also remain regarding the future available supply of green hydrogen in Europe, which might not be enough to satisfy the green energy demand from industry to align with the pathway. The significant needs for renewable electricity for its production via electrolysis, including its overall impact on power prices, should be considered.

For these reasons, studies and further pilot testing of which technology option is best suited to abate process emissions from natural gas in different segments (i.e., hydrogen or electric furnaces) must now take place, to make sure that the proper solutions are implemented. In addition, measures should be explored to advance the **rollout of competitive hydrogen production, storage, and transport infrastructure** across Europe to reduce its costs and secure its supply.

While this study estimated substantial investment costs for the industry to deliver on the 1.5°C pathway, it did not include **R&D costs** to develop and test new technologies or the **energy systems developments needed** to support such technology shifts. As such, the full cost of decarbonising aluminium production will likely be significantly higher, and therefore should be further supported via public and private funding.

Effective policy and financial support on scaling and accelerating the clean technologies that can be successfully used in the sector will therefore be essential. **R&D grants** can provide financial support for R&D initiatives focused on developing low-carbon technologies and processes for aluminium production, while **green bonds for infrastructure or contracts for difference (CfDs) schemes** could finance projects related to sustainable aluminium production with breakthrough technologies, including building or retrofitting low-carbon smelters.

[76] Statement by the President of the European Commission, Ursula von der Leyen, during her State of the European Union speech on 13 September 2023.

## 5.3 Increase scrap recovery and recycling

A key lever to reduce emissions in the aluminium sector is to **increase the proportion of recycled aluminium**, as this has a significantly lower GHG footprint than primary aluminium production. Clearly, one way to do so is through increasing the collection and treatment rates of aluminium scrap. Some of the measures[77] that can be taken in this direction include:

- Improved recycling systems and sorting methods;
- Extended producer responsibility schemes;
- Methods to divert aluminium from landfills;
- Designing products that can be easily separated, collected, and recycled;
- Encourage and incentivise aluminium alloy users to choose alloys that can be produced utilising higher scrap content.

Compared to other regions, recycling rates in Europe are already substantial, with over 90% aluminium recycled in the automotive and building sectors, and approximately 75% in the case of aluminium cans[78]. Increasing these levels remains a key lever for decarbonisation.

In addition to its role in supporting circularity, aluminium recycling only needs 5% of the energy needed to produce the primary metal. It therefore represents an important decarbonisation path which should be adequately supported and incentivised.

Nevertheless, it is important to highlight that primary aluminium production will remain important in the future, as secondary aluminium alone will not be sufficient to meet future demand, even if scrap aluminium collection rates are substantially increased. Numerous institutions, including the World Bank[79], have shown that both primary and secondary aluminium will be needed to cover the demand for aluminium to 2050 and beyond.


[77] World Economic Forum (2020). Aluminium for Climate: Exploring pathways to decarbonise the aluminium industry. Available at: https://www3.weforum.org/docs/WEF_Aluminium_for_Climate_2020.pdf
[78] European Aluminium (2022). Circular Economy Action Plan – A strategy for achieving aluminium's full potential for circular economy by 2030. Available at: https://european-aluminium.eu/wp-content/uploads/2022/08/european-aluminium-circular-aluminium-action-plan.pdf
[79] The World Bank. (2019). Climate-Smart Mining: Minerals for Climate Action. Available at: https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action

## 5.4 Incentivise and support European low-carbon and circular production capacity

Besides the presented three levers to decarbonise the aluminium sector, it is also worth mentioning the important issue of the **$CO_2$ emissions embodied in imported products**.

The full decarbonisation of the European aluminium industry also requires significant emissions reductions from imported aluminium products, ideally requiring imports to follow a similar trajectory as for European production. However, considering that the European primary aluminium footprint is less than half the global average combined with a more stringent regulatory landscape in Europe, convergence in emissions intensities between European and imported products remains unlikely in the short and medium term. Instead, a more appropriate approach for determining targets for imports is to match the GHG footprints developed within the IAI's 1.5°C scenario pathway[80]. This means that emission intensities of primary aluminium imports should not exceed 11.5 $tCO_2e/t$ Al in 2030, 2.2 $tCO_2e/t$ Al in 2040 and 0.5 $tCO_2e/t$ Al in 2050. Decarbonising the European sector therefore goes through the adoption of **informed sourcing practices and requirements** for the European industry in line with these intensity values, to ensure full decarbonisation of the European aluminium value chain.

However, the most effective way to address import-related emissions and enhance Europe's strategic autonomy in critical raw materials at the same time is to **reduce the overall need for aluminium products from outside of Europe**.

In this respect, protecting the competitiveness of the existing European facilities is crucial, and a thorough assessment is needed before fully replacing the current carbon leakage protection measures with untested new instruments (e.g. the EU Carbon Border Adjustment Mechanism - CBAM).

As noted previously, **increased production** of both secondary and primary aluminium made **in Europe** is necessary to satisfy future aluminium demands. To achieve this, policymakers must incentivise and support production capacity growth across the entire European supply chain. This is particularly the case for primary aluminium production, where current developments of closing aluminium plants and declining production capacity must be reversed. Ultimately, increased aluminium production in Europe from primary and secondary sources will help strengthen regional **material autonomy** while also replacing significant emissions associated with carbon-intensive imports, in line with the objectives of the EU Green Deal.

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# Annex

## Material conversion rates across the aluminium value chain

| Name | Value (t) | Definition | Source |
|---|---|---|---|
| **Bauxite to alumina** | 2.545 | Tonnes of *bauxite* used to produce 1 tonne of alumina in Europe | EA |
| **Bauxite to aluminium** | 4.841 | Tonnes of *bauxite* used to produce 1 tonne of primary ingot in Europe | EA |
| **Alumina to aluminium** | 1.902 | Tonnes of *alumina* used to produce 1 tonne of primary ingot in Europe | EA |
| **Anode/paste (95% anode + 5% paste) to aluminium (net use)** | 0.451 | Tonnes of *anode/paste* used to produce 1 tonne of primary aluminium in Europe | EA |
| **Inert anode to aluminium** | 0.031 | Tonnes of *inert anode* used to produce 1 tonne of primary aluminium in Europe. Assumed 1:21 ratio compared to carbon anodes | MPP (2023). Making net-zero aluminium possible: An industry-backed, 1.5°C-aligned transition strategy |
| **Aluminium to sheet** | 1.000 | Tonnes of *unscalped rolling ingots* used to produce 1 tonne of finished sheet in Europe. Assumes that process scrap (366 kg/t sheet) is remelted and reintroduced in production. | EA |
| **Aluminium to extrusion** | 1.000 | Tonnes of *extrusion ingots* used to produce 1 tonne of finished extrusion profile in Europe. Assumes that process scrap (288 kg/t extrusion) is remelted and reintroduced in production. | EA |
| **Remelting aluminium to extrusion ingot** | 1.033 | Tonnes of *input used in extrusion* cast house used in production of 1 tonne of aluminium sheet production | EA |
| **Remelting aluminium to rolling ingot** | 1.108 | Tonnes of *input used in rolling cast* house used in production of 1 tonne of aluminium extrusion product | EA |

## Key assumptions for GHG emission intensities and cost calculations

| Name | Unit | Value | Source |
|---|---|---|---|
| Process emissions | | | |
| **Direct emissions from aluminium smelting (electrolysis)** | $tCO_2e$ / tAl | 1.6040 | EU ETS Benchmark (2021). Median GHG emissions intensity of all installations in 2016/2017 |
| **CF4 (PFC) – global warming potential over 100 years (GWP100)** | $CO_2e$ | 6,630 | Greenhouse Gas Protocol (2016). Global Warming Potential Values. |
| **C2F6 – global warming potential over 100 years (GWP100)** | $CO_2e$ | 11,100 | Greenhouse Gas Protocol (2016). Global Warming Potential Values. |
| Emission factors thermal energy | | | |
| **Hard coal** | kg $CO_2e$ / MJ | 0.10 | EA, Environmental Profile Report 2018 |
| **Heavy oil** | kg $CO_2e$ / MJ | 0.09 | EA, Environmental Profile Report 2018 |
| **Natural gas** | kg $CO_2e$ / MJ | 0.06 | EA, Environmental Profile Report 2018 |
| **Diesel / Light oil** | kg $CO_2e$ / MJ | 0.08 | EA, Environmental Profile Report 2018 |
| **Steam** | kg $CO_2e$ / MJ | 0.07 | EA, Environmental Profile Report 2018 |
| Emission factors electricity use | | | |
| **EU-27 Electricity grid mix emissions intensity, GWP100** | $gCO_2e$ / kWh | 410.00 | Balmorel Energy Model |
| **European smelter electricity emissions intensity, GWP 100** | $gCO_2e$ / kWh | 130.00 | EA, Environmental Profile Report 2018 |
| **Global electricity mix emissions intensity** | $gCO_2e$ / kWh | 510.00 | Ramboll analysis based on Teske, S. (2022). Achieving the Paris Climate Agreement Goals – part 2. Available at:https://doi.org/10.1007/978-3-030-99177-7 |
| **Smelters exporting to Europe electricity emissions intensity, GWP 100** | $gCO_2e$ / kWh | 270.00 | EA, Environmental Profile Report 2018 |
| **Global smelter electricity intensity** | $gCO_2e$ / kWh | 800.00 | Ramboll analysis based on IAI 2019 data |
| **Assumed electricity emission intensity from PPA/own generation** | $gCO_2e$ / kWh | 10.43 | Ramboll estimate based on electricity supplied from 50% hydropower and 50% wind, according to Balmorel Energy Model. |

| Emission factors electricity generation | | | |
|---|---|---|---|
| **Coal** | $gCO_2e$ / kWh | 961.00 | IPCC WG3 AR5 (2018). Metrics & Methodology: Annex ii |
| **Lignite** | $gCO_2e$ / kWh | 1069.00 | World Nuclear Association (2011). Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources |
| **Natural gas** | $gCO_2e$ / kWh | 483.00 | IPCC WG3 AR5 (2018). Metrics & Methodology: Annex ii |
| **Oil** | $gCO_2e$ / kWh | 733.00 | World Nuclear Association (2011). Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources |
| **Nuclear** | $gCO_2e$ / kWh | 29.00 | World Nuclear Association (2011). Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources |
| **Low-carbon fuels (Hydrogen, ammonia, etc.)** | $gCO_2e$ / kWh | 68.00 | Assumed double of Solar PV |
| **Hydro power** | $gCO_2e$ / kWh | 6.00 | ADEME database |
| **Wind** | $gCO_2e$ / kWh | 15.00 | ADEME database |
| **Solar PV** | $gCO_2e$ / kWh | 34.00 | ADEME database |
| **Biomass** | $gCO_2e$ / kWh | 45.00 | ADEME database |
| **Geothermal** | $gCO_2e$ / kWh | 6.00 | Assumed same as hydroelectric |
| **Solar Thermal power plants** | $gCO_2e$ / kWh | 34.00 | Assumed same as Solar PV |
| **Ocean energy** | $gCO_2e$ / kWh | 124.00 | World Nuclear Association (2011). Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources |
| **Coal w. CCUS** | $gCO_2e$ / kWh | 121.00 | IPCC WG3 AR5 (2018). Metrics & Methodology: Annex ii |
| **Natural gas w. CCUS** | $gCO_2e$ / kWh | 47.00 | IPCC WG3 AR5 (2018). Metrics & Methodology: Annex ii |
| **Biomass w. CCUS** | $gCO_2e$ / kWh | -830.00 | García-Freites, S. et al (2021). The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UK's net-zero emission target |
| **Exchange rates** | | | |
| **Average yearly exchange rate USD EUR in 2022** | USD / EUR | 0.950 | European Central Bank (n.d.). US dollar (USD) |
| **Average yearly exchange rate GBP EUR in 2022** | GBP / EUR | 1.1173 | European Central Bank (n.d.). Pound sterling (GBP) |
| **USD price deflator** | Yearly index 2010-2022 | Per year | Federal Reserve Economic Data (n.d.). GDP Implicit Price Deflator in United States |
| **EURO GDP deflator** | Yearly index 2010-2022 | Per year | Federal Reserve Economic Data (n.d.). National Accounts: National Accounts Deflators: Gross Domestic Product: GDP Deflator for the Euro Area |

European Aluminium

ANYTHING BUT BASIC

European Aluminium, founded in 1981 and based in Brussels, is the voice of the aluminium industry in Europe. We actively engage with decision makers and the wider stakeholder community to promote the outstanding properties of aluminium, secure growth and optimise the contribution our metal can make to meeting Europe's sustainability challenges. Through environmental and technical expertise, economic and statistical analysis, scientific research, education and sharing of best practices, public affairs and communication activities, European Aluminium promotes the use of aluminium as a material with permanent properties that is part of the solution to achieving sustainable goals, while maintaining and improving the image of the industry, of the material and of its applications among their stakeholders. Our 100+ members include primary aluminium producers; downstream manufacturers of extruded, rolled and cast aluminium; producers of recycled aluminium and national aluminium associations are representing more than 600 plants in 30 European countries. Aluminium products are used in a wide range of markets, including automotive, transport, high-tech engineering, building, construction and packaging.

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