European Aluminium

THE INNOVATION AGENDA: Technologies for a Sustainable Aluminium Industry in Europe

January 2026

Introduction

Designated by the EU as a strategic and critical raw material, aluminium is essential to clean-energy technologies and to key industrial sectors such as automotive, construction, packaging, aerospace, digital infrastructure and defence. Every stage of Europe's economy — from the building components that shape its cities to the systems that generate, transport and store clean energy — depends on aluminium's unique combination of lightness, strength, conductivity and full recyclability.

Meeting the rising demand for low-carbon, circular and reliably sourced aluminium requires Europe to scale up a new generation of production technologies. The sector must operate under strict climate requirements, volatile energy costs and strong global competition at a time when demand for clean-energy and advanced manufacturing applications is accelerating. Yet many of the technologies needed to cut emissions and adapt to these pressures remain at pilot or early demonstration stage and are not yet commercially deployed.

To support this shift, the Innovation Hub of European Aluminium, working closely with member companies, has developed a comprehensive Innovation Agenda. It identifies the technologies, research priorities and enabling conditions required to advance low-carbon production routes, improve resource efficiency and strengthen the resilience of the aluminium value chain. Building on the study *Net-zero by 2050: Science-Based Decarbonisation Pathways for the European Aluminium Industry*, the Agenda translates Europe's climate and industrial objectives into concrete innovation pathways across six domains:

- **Electrification**
- **Hydrogen**
- **Recycling**
- **Resource Efficiency**
- **Carbon Capture**
- **Carbon-Free Production**

This executive summary outlines the core elements of the Agenda and offers a practical reference for policymakers, funding bodies, research organisations and industry. Its purpose is to align policy frameworks, guide public and private R&I investment and support the development, demonstration and scale-up of the technologies required for a competitive, circular and climate-neutral aluminium industry in Europe.

Europe's aluminium producers have the capabilities and innovation pipelines to deliver these technologies. **The priority now is to ensure that the pathways identified in this Agenda can move from research and pilot testing to full demonstration and deployment in Europe.** This involves coordinated work on standards, infrastructure, permitting, research alignment and value-chain collaboration, supported by appropriate policy and financing instruments. The Innovation Agenda sets out a clear, evidence-based route to make this possible.

[1] European Aluminium, 2023. Net-Zero by 2050: Science-based Decarbonisation Pathways for the European Aluminium Industry (Available at: https://european-aluminium.eu/blog/netzeroby2050/)

1. ELECTRIFICATION

Electrification means replacing fossil fuel–based heat and processes with electric-powered technologies, ideally supplied by renewable energy.

In aluminium production, this includes using electricity for steam generation, high-temperature heating, and process heat. While parts of the production chain are already largely electrified, other stages such as alumina refining, remelting, and downstream operations still depend on fossil fuels. Expanding electrification across these processes offers significant potential to reduce greenhouse gas emissions and accelerate the sector's path to climate neutrality.

Key Facts

- Producing primary aluminium already relies completely on electricity, using electrolysis.
- Electric technologies, when used together with Thermal Energy Storage (TES), can replace fossil fuels and make aluminium production more efficient and flexible. TES stores heat made from renewable electricity so it can be used later — even when the sun isn't shining or the wind isn't blowing.
- Smelters with emerging flexible operating strategies could play an important role in supporting power systems with increasing shares of renewables. Early assessments indicate that the ability to shift consumption by several tens of megawatts for sustained periods could offer grid services typically associated with storage. As this concept matures, incorporating such industrial flexibility into system planning has the potential to reduce both the cost and complexity of expanding renewable energy systems.

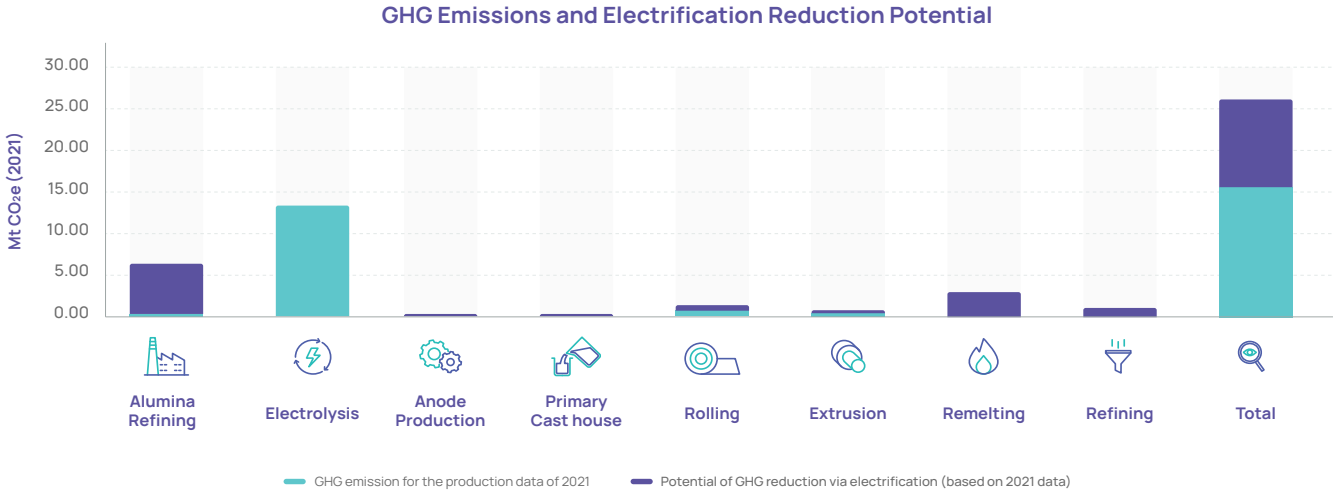


Figure 1 Greenhouse gas (GHG) emissions and potential GHG reduction through electrification across various stages of the aluminium production process, from [1].

Main Barriers

- Limited technological maturity for several high-temperature industrial processes.
- Scaling up from pilot to full industrial operation remains complex and costly.
- High capital and operating costs, with uncertain long-term electricity prices, make business cases difficult.
- Dependence on affordable, stable renewable electricity and adequate energy storage.
- Grid limitations and regional disparities in renewable energy infrastructure slow deployment.

RESEARCH & INNOVATION PRIORITIES

Solutions

Electric Furnaces

Collaboration with technology providers to develop and validate electric furnace technologies for alumina processing, melting, remelting, and downstream applications — focusing on high temperature performance, energy efficiency, and operational flexibility.

Thermal Energy Storage (TES)

Development of efficient thermal storage systems optimised for large-scale industrial applications, grid integration, and reducing infrastructure costs.

Heat Efficiency

Research into systems that recover and reuse waste heat from industrial processes to reduce overall energy demand and maximise the benefits of electrification across production stages.

Mechanical Vapour Recompression (MVR)

Demonstration projects for industrial-scale validation, specifically addressing high-temperature integration and reliability.

Ensuring Flexible and Green Energy
HORIZONTAL ENABLER

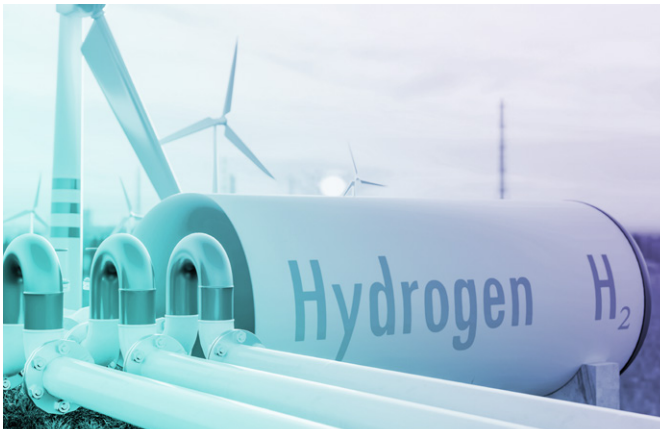
Research into policy frameworks, market incentives, and infrastructure improvements necessary to secure stable, affordable renewable electricity supply and enhanced grid capacity across Europe.

2. HYDROGEN AS FUEL

Hydrogen as a fuel presents a complementary decarbonisation route for the aluminium industry, particularly for high-temperature processes where electrification remains technically or economically challenging.

When produced from low-carbon energy sources, hydrogen offers an alternative to natural gas.

As hydrogen combustion emits only water vapour, it has the potential to significantly reduce CO_2 emissions, although deployment faces infrastructure, economic, and technical challenges.



Key Facts

- When there is a surplus of renewable energy produced, on-site hydrogen generation via electrolysis can convert this excess electricity into hydrogen, store it for later use, and reduce the need for long-distance transport.
- Hybrid fuel-switching solutions can combine hydrogen and natural gas, allowing a gradual transition and greater operational flexibility while infrastructure and supply chains mature.
- Hydrogen can also enable new industrial synergies, linking aluminium production with emerging hydrogen hubs and with other industries that use hydrogen in their processes, such as steel and chemicals.
- Hydrogen should complement, not replace, electrification: wherever direct electrification is technically and economically viable, it remains the most efficient and cost-effective route to decarbonisation. In that respect, hydrogen production from natural gas (plasmalysis) is an alternative to production from water electrolysis that should be explored.

Main Barriers

- High-temperature hydrogen flames can accelerate corrosion through the increase of the concentration of water vapour, affecting equipment durability. Greater generation of nitrogen oxides (NO_x) can affect air quality.
- Existing safety procedures and standards are designed for natural gas. Hydrogen introduces new and unforeseen risks, and industries have limited experience with its handling and safety requirements.
- Hydrogen production, retrofitting of equipment, and on-site storage involve significant investment and can raise operating costs compared to conventional systems.
- The future price and accessibility of low-carbon hydrogen vary widely across Europe, creating uncertainty for planning and investment.
- Incomplete or inconsistent permitting frameworks delay project approvals and slow down large-scale deployment.

RESEARCH & INNOVATION PRIORITIES

Technology

Hydrogen Combustion Systems

Better understand and minimise NO_x formation, water vapour, and corrosion risks linked to high-temperature hydrogen combustion.

Safety Systems, Standards & Training

Develop hydrogen-specific safety concepts, detection and leak-prevention systems, and operational protocols; Support the development of industrial safety standards and training programmes, to ensure safe handling and operation.

Hydrogen Infrastructure & Storage

HORIZONTAL ENABLER

Scale up safe hydrogen storage technologies and strengthen connections to regional hydrogen hubs through EU-supported transport and infrastructure projects.

Policy & Certification Mechanisms

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Develop comprehensive policy and certification frameworks that support the deployment of low-carbon hydrogen and ensure fair and consistent emission standards.

3. RECYCLING

Recycling is at the heart of Europe's aluminium value chain and a key pillar of a circular and low-carbon industry. By keeping aluminium in use and recovering it at the end of its life, the sector cuts emissions, saves energy, and reduces dependence on imported raw materials. Expanding high-quality recycling can meet growing demand while supporting Europe's goals for resource efficiency, strategic autonomy, and industrial decarbonisation.

Key Facts

- Recycling aluminium uses around 95% less energy than producing primary aluminium, making it one of the most efficient materials in the circular economy.
- Around 75% of all aluminium ever produced is still in use today, thanks to its durability and high recyclability.
- Europe leads globally in aluminium recycling, achieving recovery rates of about 90% in transport and construction and around 75% in beverage cans.
- Aluminium can be recycled indefinitely without losing its material properties or quality.
- Recycled aluminium already accounts for more than 60% of Europe's total production, significantly reducing emissions and energy demand across the value chain.

Main Barriers

- The wide variety of aluminium alloys makes sorting and separation more difficult, reducing the efficiency and quality of recycling.
- Current melt purification and neutralisation methods are not yet mature or scalable enough to handle varying levels of contamination.
- Tracking and verifying recycled aluminium across complex supply chains remains difficult due to the lack of interoperable digital systems.
- Large volumes of aluminium scrap leave Europe for processing abroad, limiting strategic access to secondary raw materials.
- Collection, sorting, and recycling infrastructure are supported by inconsistent policy and funding mechanisms across Member States.
- Different levels of technology, regulation, and expertise across countries lead to uneven recycling performance within Europe.

RESEARCH & INNOVATION PRIORITIES

Research & enabling areas

Design for Recyclability

- Review and develop new alloy specifications that are based on performance criteria rather than just composition, allowing for greater flexibility and uptake of recycled aluminium alloys in high-value applications.
- Develop product designs that maximise ease and quality of recycling.
- Develop and deploy interoperable digital tools to trace recycled aluminium across supply chains, ensuring transparency, quality assurance, and improved material flow management.

Advanced Sorting and Scrap Preparation

Scale-up and industrial validation of advanced sorting and scrap preparation (e.g., pre-treatment, separation, cleaning) technologies for increased purity and efficiency in recycling diverse aluminium scrap streams, focusing on the ability to separate scrap into different quality/purity grades.

Aluminium Melt Purification and Neutralisation Techniques

Demonstration of cost-effective purification technologies and neutralisation techniques for varied contamination levels, promoting greater use of recycled aluminium in high-quality applications.

Collaboration and Value Chain Integration

Strengthen cooperation among product manufacturers, recyclers, collectors, and waste management actors to optimise recycling processes, improve material flows, and increase overall system efficiency.

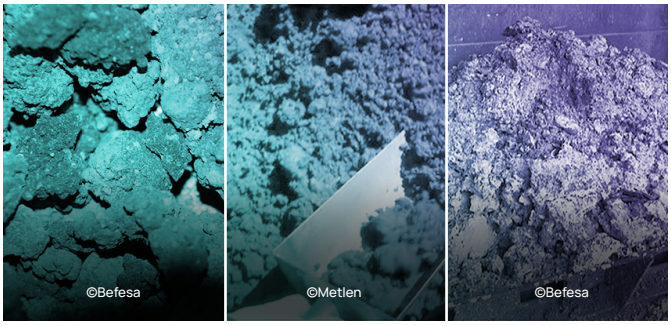
Policy Incentives

HORIZONTAL ENABLER

Investigate effective policy measures that act as horizontal enablers across all areas, fostering a circular economy. This includes reviewing policy/regulatory levers that can enhance recycling infrastructure investment and scrap retention within the EU, and specifically focus on policies that make the supply chain profitable rather than just direct economic incentives.

4. RESOURCE EFFICIENCY

The European aluminium value chain generates significant streams of waste and by-products (see table below). These materials offer an opportunity to shift from conventional management practices toward resource-efficient business models. Within this framework, the sector is actively developing and assessing technically feasible and economically viable solutions using integrated approaches and diverse technologies to safely and sustainably valorise these streams.



Main waste and by-product streams along the aluminium value chain

Waste & by-products	Annual production, Mt*	Process segment
Bauxite residue	5.9	alumina refining
Spent pot lining	0.1	electrolysis (aluminium smelting)
Aluminium dross	0.3	ingot casting, recycling (remelting, refining)
Aluminium salt slags	1.0-1.2	recycling (remelting)
Refractories	0.02	aluminium casthouse, anode/paste, aluminium smelting

* Data from the Environmental Profile Report (2024) on the primary and secondary aluminium production.

Key Facts

- The industry generates over 7 Mt/year of residues (e.g., bauxite residue, spent pot lining, aluminium dross, and salt slags), representing a major untapped resource for circular use.
- Advanced valorisation approaches can convert these streams into high-value materials, reduce landfill dependency, and foster cross-sector collaboration with cement, steel, and other industries, supporting climate neutrality and long-term competitiveness.

Main Barriers

- Heterogeneous waste streams require advanced processing and quality control to realise large-scale valorisation potential.
- Inconsistent regulatory frameworks limit cross-border reuse and circularity, slowing adoption of wider resource-efficient business model solutions.
- High processing and logistics costs hinder scaling of valorisation pathways without targeted funding and policy support (incentives).
- Public acceptance, stakeholder engagement, and land-use considerations can constrain deployment of new processing and valorisation infrastructure.

RESEARCH & INNOVATION PRIORITIES

Research & enabling areas

Valorisation technologies & industrial deployment

Further advance robust, cost-effective technologies and integrate them into existing production systems through process optimisation for industrial-scale validation.

Cross-sectoral collaboration & demonstration

Strengthen collaboration with partners (for example in sectors such as cement, steel, ceramic, refractory materials, metal recovery and other relevant industries identified based on priority aluminium key waste/by-product streams) and develop joint large-scale demonstration initiatives under the industrial symbiosis concept.

Standardisation

Develop standards to ensure quality, regulatory compliance, and facilitate industrial and market acceptance of new products resulting from waste/by-products valorisation.

Proper regulatory framework

Develop EU-harmonised End-of-Waste criteria for the identified priority streams to ensure regulatory certainty, safe transport, and acceptance by downstream industries.

5. CARBON-FREE PRIMARY PRODUCTION

The European aluminium sector is advancing transformative innovations to enhance sustainability, through breakthrough and sustainable technologies and processes with emphasis on:

- Alternative Al_2O_3-bearing feedstocks enabling smelter-grade, low-carbon or carbon-free alumina production, complementing the existing bauxite-based value chain.
- Next-generation aluminium smelting based on inert anode technology and carbon-chlorination process with Cl^- / CO_2 closed-loop system.

Key Facts

Alternative alumina production

- Alternative chemical routes based on non-bauxite Al_2O_3-bearing feedstocks enhance raw materials diversification, reduce exposure to geopolitical and resource constraints and enhance the resilience and competitiveness of the European alumina value chain.
- Developing new chemical refining pathways can significantly improve the environmental performance of alumina production by decoupling it from the carbon-intensive, residue-generating conventional Bayer process.

Next-generation aluminium smelting

- Inert anode and carbon-chlorination technologies can eliminate the direct process emissions from carbon oxidation and perfluorocarbon (PFC) formation, fully removing Scope 1 emissions. When coupled with carbon-free or low-carbon electricity, Scope 1 and Scope 2 electrolysis emissions can be eliminated.
- Projects confirm feasibility at pilot scale, but sustained R&D and major investments are needed to support large-scale deployment.

Main Barriers

Alternative alumina production

- Advanced extraction and purification under acidic conditions is required ensure product quality and process efficiency, reflecting the compositional variability of alternative feedstocks in new refining developments.
- Regulatory compliance and permitting for implementation require new environmental and safety requirements, including benchmarking, validation, and verification.
- Limited R&D funding for pilot and demonstration projects slows progress in proving technical feasibility and cost competitiveness.
- Social acceptance, workforce adaptation, and land-use planning can constrain deployment, as new refining or mining sites could raise public concerns that require proactive engagement and community involvement.

Main Barriers

Inert anodes

- Inert anode technology has demonstrated promising electrochemical performance at pilot scale, though further validation is required to ensure stability, efficiency, and reliability under industrial operating conditions.
- High capital intensity, increases in operating costs, and extended payback periods.
- Limited access to low-carbon, affordable and stable electricity is affecting both the operational feasibility and the true decarbonisation potential of inert-anode technology.
- Permitting frameworks for inert-anode technology is needed along with industrial safety standards to facilitate approval process.
- Large-scale deployment will depend on strong collaboration (i.e. technology developers, smelter operators, and equipment suppliers) ensuring that new technologies can be effectively integrated within both existing and future production systems.

Carbon-chlorination

- Scaling to industrial operations requires further understanding of the chemical system, along with adaptation of infrastructure for element compatibility and closed-loop chlorination–carbon capture systems to ensure reliable and efficient performance.
- Industrial deployment demands substantial capital investment, as development focuses on new production facilities. Securing funding for pilot and commercial phases is essential to de-risk large-scale adoption.
- Need for proper handling protocols and dedicated industrial safety standards to ensure safe operation and regulatory compliance.

RESEARCH & INNOVATION PRIORITIES

ALTERNATIVE ALUMINA PRODUCTION

Research & enabling areas

Refining technologies

Advance and optimise efficient, low-impact extraction and purification routes for non-bauxite feedstocks to produce smelter-grade alumina.

Deployment

Design, build, and operate pilot and demonstration plants to validate process efficiency, assess environmental performance at industrial scale, and confirm cost competitiveness.

Regulatory and environmental alignment

Develop and harmonise permitting frameworks and ensure compliance in line with EU sustainability objectives.

Societal acceptance and regional transition

Strengthen research on social acceptance, land-use management, and stakeholder engagement for new mining and refining projects, supporting transparent dialogue and responsible regional development.

INERT ANODES

Research & enabling areas

Advanced electrolytic cell

Design and optimise the electrolytic cell technology to enhance electrical conductivity, process stability, and energy efficiency, supported by advanced monitoring and control systems for industrial operation.

Pilot and demonstration

Scale up to industrial-scale demonstrations to validate long-term performance, optimise process integration, and de-risk capital investment.

Regulatory and permitting alignment

Support all relevant activities (standards, protocols, etc.) to streamline approval processes and ensure safe, compliant deployment.

Value chain integration and collaboration

Strengthen cooperation across the entire value chain and innovation ecosystem (from material developers and technology providers to smelter operators and energy suppliers) to accelerate technology transfer and enable coordinated scale-up and industrial deployment.

CARBON-CHLORINATION

Research & enabling areas

Process optimisation and system integration

Develop and optimise industrial-scale process designs, including advanced monitoring, impurity control, and integrated chlorine/carbon recovery systems, to demonstrate reliable, high-efficiency operation and enable scale-up.

Demonstration and industrial validation

Extend pilot-scale results to large-scale demonstrators to validate performance, benchmark environmental outcomes, and assess economic viability for new production sites.

Safety and environmental standards

Develop robust protocols for chemical handling, process monitoring, and emissions control to ensure safe and sustainable industrial adoption.

6. CARBON CAPTURE

Carbon Capture and Storage (CCS) provides a complementary pathway to decarbonise parts of the aluminium value chain where process- and combustion-related CO_2 emissions are technically challenging or costly to eliminate through other solutions. CCS can help tackle hard-to-abate sources while supporting the sector's long-term alignment with EU climate objectives.

Key Facts

- Deployment of CCS in the aluminium sector is at an early stage.
- Early research, pilot testing, and demonstration are essential to develop efficient, cost-effective, and scalable CCS solutions.

Main Barriers

- Developing and validating CO_2 capture systems specifically tailored to aluminium diluted CO_2 emissions originating from primary smelters is technically complex, requiring specialised R&D.
- Applying carbon capture for melting furnaces require the switch to oxy-fuel burner technologies involving already significant investments beyond capture technologies.
- High capture costs and energy demands make implementation challenging without access to affordable low-carbon energy and dedicated funding mechanisms.
- Availability of verifiable storage sites remains uneven across Europe requires further coordinated regulatory and permitting frameworks.
- Economically viable CO_2 utilisation pathways require further research to complement storage options.
- Limited access to CO_2 transport infrastructure, especially from remote recycling aluminium plants, continues to hinder the development of cost-effective CCUS value chains.

RESEARCH & INNOVATION PRIORITIES

Research & enabling areas

CO_2 capture technology development

Develop and demonstrate advanced carbon capture technologies (solvents, sorbents, membranes, and/or modular components) tailored to particulate and operational conditions in aluminium production.

CCS industrial integration, validation & demonstration

Develop aluminium-specific pilot and demonstration projects to validate capture performance, energy demand, and cost-effectiveness under real operating conditions (incl. optimisation of heat recovery and integration with existing plant systems).

CO_2 storage access & monitoring

Ensure access to safe, cost-efficient, and verifiable CO_2 storage sites, supported by accelerated permitting as well as robust protocols and standards, involving both industry and national/regional authorities.

CO_2 utilisation

Advance on economically viable utilisation pathways that could complement storage options, and expand downstream opportunities for captured CO_2.

CO_2 transport infrastructure & cross-value-chain collaboration

Strengthen collaboration among aluminium producers, capture technology developers, energy providers, CO_2 transport–storage operators together with regional authorities to develop transport infrastructure, accelerate innovation and scale-up, and enable cost-effective deployment across the full CCUS chain.

Call for action: Investing in Aluminium Innovation for Europe's Future

To unlock this potential, Europe needs dedicated funding and coordinated policy support that reflects aluminium's specific innovation needs. Targeted action in areas such as low-carbon production, recycling, process electrification, and carbon management will reduce emissions, strengthen resource efficiency, and create high-quality green jobs across Europe.

Supporting aluminium innovation is not an investment in one industry; it is essential for Europe's strategic autonomy and technological capability. Aluminium is a strategic and critical raw material, and the ability to produce low-carbon, circular aluminium domestically is central to clean energy deployment, electric mobility, digital infrastructure and defence. Where innovation is demonstrated and deployed will determine where future aluminium production is located. Without targeted support to scale these technologies in Europe, new investments will move to regions already advancing them, weakening Europe's industrial base and limiting access to the sustainable aluminium needed for a resilient, competitive and climate-neutral future.

That's why aluminium innovation must be embedded in Europe's clean industrial strategy through coordinated EU and national funding, predictable regulatory pathways for pilot and first-of-a-kind projects and strong collaboration across the value chain. **Acting now lets Europe lead, not follow.**

Our Innovation Hub

The European aluminium industry plays a leading role as a cross-sector innovation catalyst for the circular economy, decarbonisation, and disruptive technologies. From advancing packaging circularity and process innovation to finding new applications for production residues, we are committed to unlocking the full potential of aluminium to support Europe's sustainability transition.

To channel this momentum, European Aluminium created the Innovation Hub, bringing together members, the wider value chain, and RD&I partners. The Hub is a collaborative platform where technological challenges can be addressed at a pre-competitive level and translated into concrete projects.

By connecting industry expertise with research capabilities and funding opportunities, the Innovation Hub accelerates the development of clean, circular solutions for aluminium and for the sectors that rely on it.

What We Do

Initiate EU-Projects

The Innovation Hub facilitates the development of collaborative project proposals for its members and joins proposals under development, especially EU project proposals submitted to the EU's Horizon Europe research and innovation funding programme.

Participate in Public-Private Partnerships

The Innovation Hub leverages its extensive stakeholder network, including policymakers, experts, and research institutes, to participate in relevant Public-Private Partnerships. Active participation in these initiatives is essential to shaping the future innovation landscape, influencing research priorities, and ensuring that aluminium-related solutions contribute to Europe's broader sustainability and industrial competitiveness goals.

Develop collaborative studies for its members

To address the priority topics defined by its members, the Innovation Hub organises collaborative studies. These studies are developed based on a tendering process to select the best external contributor, ensuring that technological challenges are effectively addressed at a precompetitive level while contributing to the sustainability targets of the aluminium industry.

Connecting to the research community

The Innovation Hub maintains close ties with Europe's leading Research and Technology Organisations (RTOs) and innovation stakeholders through a variety of activities, including Innovation Workshops, webinars, and knowledge-sharing sessions. These initiatives aim to foster collaboration with the aluminium industry, facilitate the exchange of expertise, and stimulate the development of new research projects.

Are you interested in getting more information about our Innovation Hub? Contact us at **innovation@european-aluminium.eu.**

About European Aluminium

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. Our 100+ members include primary aluminium producers; downstream manufacturers of extruded, rolled and cast aluminium; producers of recycled aluminium and national aluminium associations, 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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ANYTHING BUT BASIC