European Aluminum's Innovation Hub: Enhancing bauxite residue valorization pathways through collaborative EU projects

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Abstract

In 2015, European Aluminum established its Innovation Hub as a collaborative platform to accelerate the transformation to a clean and circular Europe for aluminum producers and cross-sector partners. Since then, the Innovation Hub of European Aluminum plays a crucial role in facilitating the development of European Union (EU) funded collaborative projects across the aluminum value chain by bringing together the necessary participants from the membership, the broader industry, and Research, Development & Innovation organizations. Focusing on the upstream part of the aluminum value chain, one of the most significant challenges is related to the bauxite residue (BR) generation as well as its environmentally and socially acceptable valorization pathways to reduce reliance on landfilling. European alumina refineries are actively seeking innovative solutions to transform this challenge into an opportunity by developing environmentally safe and economically viable solutions which could possibly result in market-accepted BR-based products. Within this context, H2020 projects RemovAL (Grant Agreement no. 776469-completed in April 2023) and ReActiv (Grant Agreement no. 958208-in progress) aim to promote the combination of multiple technologies and establish industrial symbiotic schemes, especially with the construction sector. These cross-sectoral projects seek to overcome environmental issues and technological barriers in a financially efficient manner, ultimately facilitating meaningful BR valorization. As part of both consortia, the Innovation Hub facilitates the cross-sectoral collaboration and advocates for the need to adapt the current EU legislation for enabling the proper valorization of bauxite residue under the overall concept of circular economy.

Keywords: Bauxite residue, Near-zero-waste, Circular economy, Industrial symbiosis, Regulatory framework.

1. Introduction

Alumina refineries play a crucial role in the aluminum value chain, yet they face a significant challenge: the environmentally and socially safe management of bauxite residue (BR), also known as processed bauxite or red mud. The European Union (EU) currently has active alumina plants operating in various countries such as Germany, Greece, Ireland, and Spain, while alumina production has been temporarily suspended in Romania. Neighboring countries such as Bosnia-Herzegovina and Turkey produce alumina, whereas two alumina refineries in Ukraine (Mykolaiv and Zaporozhye) have been shut down.

In 2021, EU-27 produced approximately 6 Mt of alumina, compared to the global production of 138 Mt during the same period. In addition, an estimated 5 Mt of BR were generated in the EU-27, with most being stored in landfills. Notably, significant BR legacy sites exist throughout Europe, including France, Italy, Germany, Hungary, Montenegro, Slovenia, Croatia, Bosnia & Herzegovina, Scotland and elsewhere. The cumulative stockpile of BR in the EU exceeds 250 Mt (dry basis) [1].

Despite the recent decline in BR generation at an EU level, global production reached around 160 Mt in 2021, representing a significant increase from around 60 Mt in 2001. However, this increase occurred without a proportional rise in supply reuse.

Table 1. Production of alumina and bauxite residue in Europe & Turkey [1].

Alumina producer*	Location / Country	Estimated alumina production (ktpa)	Estimated BR production (ktpa)
Aughinish Alumina Ltd (AAL)	Limerick / Ireland	1 900	1 500
Alcoa	San Ciprian / Spain	1 500	1 350
Alum S.A.**	Tulcea / Romania	500	450
Alumina d.o.o	Birac / Bosnia-Herzegovina	600	550
Aluminium Oxid Stade	Stade / Germany	1,050	950
Eti Aluminiyum	Seydişehir / Turkey	490	440
Metlen Energy & Metals	Agios Nikolaos / Greece	860	775
** The Gardanne plant in France has been excluded from consideration.*			
*** The alumina production is temporarily suspended, thus BR generation has stopped.*			

In response, the European alumina refineries are actively seeking innovative and financially viable solutions to transform the challenge of BR into an opportunity by developing environmentally safe and market-accepted BR-based products, following the EU's circular economy principles.

Within the complex landscape of BR management, cross-sectoral collaboration becomes essential in the quest for comprehensive solutions. European Aluminum's Innovation Hub stands as a pivotal force in fostering such collaboration and catalyzing innovation within the aluminum industry. Serving as a dynamic platform for industry-wide cooperation and knowledge dissemination, the Innovation Hub brings together diverse stakeholders, enabling them to exchange insights, investigate novel technologies, and explore holistic valorization pathways. In doing so, it not only addresses immediate challenges but also significantly contributes to the long-term competitiveness and sustainability of the European aluminum sector.

2. Current Bauxite Residue Management in Europe: Indicative Case Studies from EU Alumina Refineries

All BR generated in the EU is deposited in Bauxite Residue Storage Facilities (BRSFs). The processes used for handling and storage of BR are determined by factors, such as the age of the refinery, land availability, proximity to the sea, local topography, climate, logistics, nature of the residue and regulations. Over time, major improvements have been made in the design and management of residue facilities to minimize safety risks and environment risks. Table 2 presents indicative BR handling practices from active EU alumina refineries. It is noted that the BR processed using the Best Available Techniques (BAT) has been classified as a non-hazardous waste.

Table 2. Indicative handling practices for BR in active European alumina refineries.

BR Farming* at Aughinish Alumina Ltd (AAL), Limerick, Ireland BR is deposited in a designed area where it is exposed to atmospheric conditions, naturally carbonated, and dried. Farming of BR involves the use of specific residue farming equipment, called "Amphirols", which can operate on wet and dry BR, along with other agricultural machinery. The "farmed BR" from AAL refinery can achieve a solid content of 72 to 75 wt.% with a pH below 11.5.	
BR filtered at Metlen Energy & Metals (formerly MYTILINEOS), Agios Nikolaos, Greece** The BR slurry undergoes high-pressure filtration, and the resulting cake, referred to as "Filtered BR" has a solid content of about 75 wt.% constituting a moist material that can be transported by truck or conveyor belt. Natural weathering of the filter cake for a period of 30 days increases the solid content of 78 to 82 wt.% (depending on weather conditions).	
Slurry BR in tailing dams (lagooning) at Aluminium Oxid Stade, Germany AOS in Stade filters the residue using drum filters, washes it using condensates, and then pumps the material in a slurry form to holding ponds. While this residue has a higher water content (approximately 40 wt.%) than BAT farmed or press filtered BR, it has a low soda content and consequently a less alkaline pH value.	
** The bauxite residue farming technique is a Best Available Technique (BAT 29, following the JRC Best Available Techniques Reference Document for the Management of Waste from Extractive Industries in accordance with Directive 2006/21/EC)*	
*** The filtration method by mechanical compression is a Best Available Technique (BAT 57 as detailed in the Commission implementing decision 2016/1032 of 13 June 2016 establishing Best Available Techniques conclusions under EU Directive 2010/75/EU)*	

The composition of BR is influenced by its mineralogical constituents and processing conditions, resulting in elevated concentrations of various elements and mineralogical phases, as well as variable pH levels (Table 3).

Table 3. Typical composition of BR in Europe [2].

Chemical composition	Range %	Main mineralogical phases
Fe_2O_3	30-50	hematite, magnetite, aluminium-goethite, ilmenite
Al_2O_3	15-25	boehmite, gibbsite, diaspore, aluminium-goethite, cancrinite, sodalite, hydrogarnet
CaO	1-9	calcium cancrinite, hydrogarnet, perovskite, katoite, calcite
SiO_2	4-15	quartz, bayer sodalite
TiO_2	0-17	titanium dioxide, rutile, ilmenite, anatase, brookite, perovskite
Na_2O	2-10*	sodium hydroxide, bayer sodalite
**Depending on the BR management practice applied*		

3. Drivers and Barriers for Innovative BR Valorization

As previously demonstrated, safe BR disposal methods have improved enormously in the last two decades globally. However, the valorization of BR remains marginal, despite years of significant

research, technology, and development (RTD) efforts related to various applications, as evidenced by more than 734 patents since 1964 and 4757 scientific publications [3, 4]. These efforts have explored aspects such as applications, management, mining processes, disposal, and the extraction of valuable metals. Currently, only 3 % of annual BR production is utilized in cement, iron production, or other applications worldwide, indicating the willingness of various sectors to collaborate symbiotically, while the remainder is contained in special facilities known as Bauxite Residue Disposal Areas (BRDA).

An exemption to this trend is the valorization of more than 330 kt of Greek BR as a raw material for clinker cement substitution at rates of 1.5–3 % since 2012. The use of filter-presses to convert BR slurry into a filter cake or residue farming are considered facilitators for any valorization scenario. The main barriers to large scale (industrial) valorization of BR, which explain why clear-cut cases are rare and can only be applied to a fraction of the produced BR in a refinery, are identified below.

Technical: Soda content and moisture are the most common challenges. It is noted that in the case of BR valorization in cement production, neither of these factors is crucial for additions up to 1–1.5 %.

Legislative: Reuse and transport of BR are hampered by the ambiguity of its European Waste Codes (EWC) classification, and the complexity imposed by EU waste transfer regulations, including specific permits from all involved parties. Cross-border transport is even more complicated. Moreover, incentives for industries to prioritize the use of industrial by-products over virgin raw materials would also be beneficial. Establishing a more harmonized regulatory framework at the EU level would facilitate the deployment of the most optimized solution for BR valorization.

Financial: No single, stand-alone solution seems to be viable for reusing the vast amounts of BR produced. Pooling multiple solutions together and optimizing them in an integrated manner is the only way to render bauxite residue reuse viable from an economical point of view and acceptable for industry. Moreover, logistics (i.e. distance, means of transport) and potential gate fees are important factors.

Social: Local communities are often eager to protest against any plant treating by-products or wastes “in their backyard.”

Within this framework, European Aluminum, through its Innovation Hub, is actively involved in two cross-sectoral Innovation Action projects co-funded by the European Union: RemovAL (Grant Agreement no. 776469) [5] and ReActiv (Grant Agreement no. 958208) [6]. These projects combine and optimize multiple technologies in an integrated manner to make BR valorization economically viable and acceptable to the industry, while minimizing the risk for the environment and society.

3.1 EU RemovAL Project

The EU RemovAL project [5] was initiated in May 2018 and concluded in April 2023. As a comprehensive scale-up project, its goals were to address environmental concerns and technological barriers of BR reuse/valorization. It aimed to achieve this by integrating and advancing existing technologies for the sustainable processing of BR and other revenue-generating by-products. Additionally, it focused on enhancing economic viability by combining and integrating proposed stand-alone solutions.

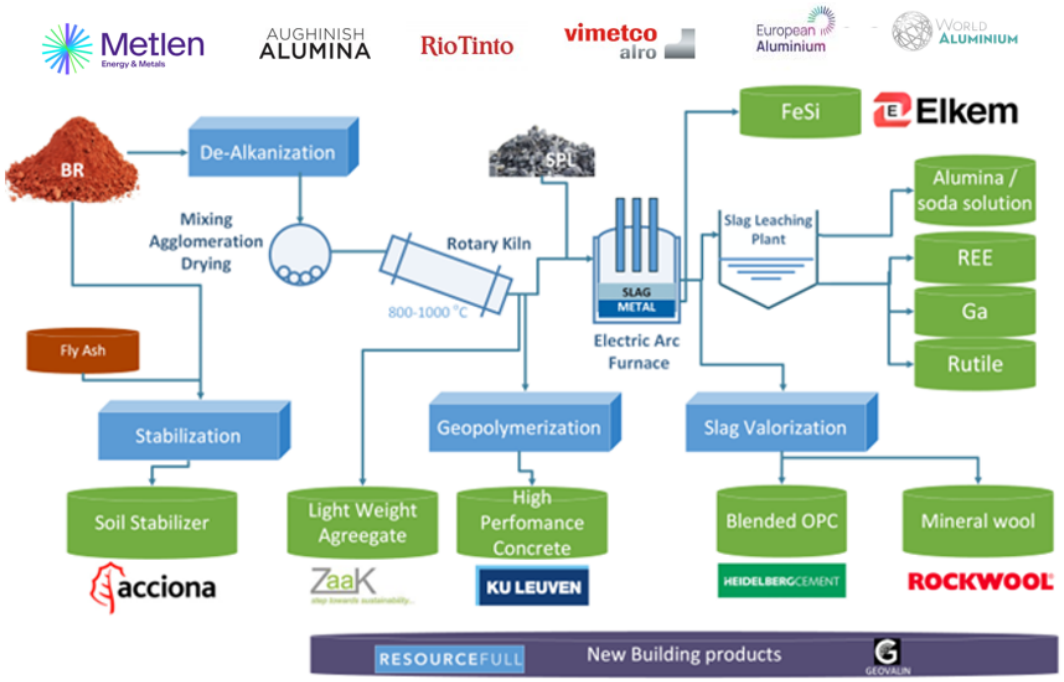

Figure 1. RemovAL concept and consortium.

Six pilot-scale demonstrations have been developed and evaluated within the framework of the EU RemovAL project (Table 4). These technologies can be adjusted to accommodate various compositions of BR found throughout Europe.

Table 4. Pilot scale demonstrations.

Pilot 1	Demonstrate at pilot scale the de-alkalization technology to remove alkali content from BR at levels below 0.5 wt.%, making it suitable for various applications.
Pilot 2	Demonstrate the use of processed BR as a green soil stabilizer for civil works applications though the stabilization of BR with other industrial by-products.
Pilot 3	Demonstrate at pilot scale the production of lightweight aggregates and high-performance binders through different palletization and thermal treatments of BR.
Pilot 4	Demonstrate at pilot scale the production of ferro-silicon alloy from Electric Arc Furnace (EAF) co-processing of BR with other industrial by-products, such as Spent Pot Lining (SPL) from aluminum primary production.
Pilot 5	Demonstrate the production of metallic iron from processing BR with other industrial by-products using a prototype microwave rotary kiln furnace.
Pilot 6	Demonstrate the production of REE (rare-earth element) concentrate, Ga concentrate, alumina/soda solution, and rutile concentrate from the hydrometallurgical processing of engineered slags/sinters produced in RemovAL pyrometallurgical pilot plants. Ga is co-extracted both from the slag and the Bayer liquor.

The overall effort is supported by a comprehensive feasibility study conducted at each of the refinery sites for the demonstrated technologies. Most of the processes showed potential and their economic viability depends on various factors such as product price, capital investment, disposal cost, and transportation distance. As a demonstration of the production of new marketable building products, Metlen Energy & Metals working with an architect to construct “The House of Bauxite” at the center of the Aspra Spitia community, adjacent to the Metlen Energy & Metals aluminum plant in Greece. This multipurpose construction, covering an area of 120 m^2, serves as a physical and virtual exhibition of materials and technologies produced by RemovAL (Figure 2).

Figure 2. Part of "The House of Bauxite" external wall made from BR brick slips (ResourceFull), while some of Removal partners are sitting on bench made from BR high strength binder (KU Leuven).

3.2 EU ReActiv Project

The EU ReActiv project [6] was initiated in November 2020 and is currently ongoing, scheduled to conclude in April 2025. This initiative aims to demonstrate the conversion of BR into a new Supplementary Cementitious Material (SCM), capable of substituting up to 30 wt.% of clinker in cement production, thereby showcasing a sustainable and resource-efficient approach. To achieve its objectives the ReActiv project brings together the global leader in cement production, the largest alumina producers, top research institutes and technology providers with significant expertise in the field (Figure 3).

Figure 3. ReActiv concept and consortium.

Its significance is reinforced by the projected decline in the availability of conventional SCMs, such as fly ash and blast-furnace slags, which have long been components in the construction industry. As these traditional materials will become scarcer, the abundant supply of BR across Europe positions it as a promising and strategic alternative which can help deliver the cement and alumina industries' circularity and decarbonization ambition.

In addition to the previous studies evaluating the potential of BR as a SCM [7], the EU ReActiv project aims to further advance the valorization of BR in cement. This is achieved through the parallel investigation of three different processing routes (Figure 4) aiming at modifying its properties. These three processing routes are applicable to de-alkalized and low moisture content BR. It is noted that the BR de-alkalization technology has been demonstrated by AAL under RemovAL, whereas the process is subjected to further optimization under ReActiv project to achieve a low sodium content ($Na_2O \leq 0.5$ %).

Figure 4. ReActiv processing routes to develop BR-based SCMs.

3.2.1 BR Thermal Activation with Kaolinite Clay (Co-Calcination)

This process involves blending BR with additives, such as kaolinitic clays, readily available to alumina refineries. It aims to produce performance-compliant SCM at relatively low temperatures (650–800 °C) [8].

3.2.2 BR Carbothermic Vitrification for Iron-Rich SCM

Research conducted by Giels et al. [9] indicates that BR can be chemically and thermally transformed into a reactive semi-vitrified precursor, which can be used to produce inorganic polymers. The composition of the amorphous phase and thus the degree of polymerization can vary significantly depending on the additives used.

3.2.3 BR Smelting for Iron-Free SCM

This proposed processing route aims to co-produce metallic iron and BR slag for use as SCM. Previous research (EU funded ENEXAL [10] & RemovAL projects) has demonstrated the potential to generate pig iron from BR using EAF processing. Furthermore, the smelting process can reduce the initial soda content by up to 40 %, resulting in a decrease in chemical variability. The remaining major elements in the BR, primarily Ca, Si, Al, and Ti, contribute to the formation of a slag suitable for use as an SCM [11].

4. European Aluminum's Innovation Hub as key enabler to RemovAL and ReActiv

European Aluminum's Innovation Hub mainly deals with the dissemination/communication aspects especially towards the aluminum sector, industrial exploitation via sector mapping and policy framework analysis enabling the deployment of relevant innovation. By initiating targeted actions, the Innovation Hub adds significant value to these projects, facilitating the implementation of BR valorization pathways.

4.1 Engaging Stakeholders for Relevant Actions

4.1.1 Alumina Task Force

For the purposes of the EU RemovAL and ReActiv projects, European Aluminum engaged key European alumina players in a stakeholder group, namely Alumina Task Force (TF) on EU

projects. This group of stakeholders, coordinated by European Aluminum and launched in March 2021, includes AAL, Alcoa, Hydro, Metlen Energy & Metals, Rio Tinto, Alum, and the International Aluminum Institute (IAI). In September 2022, AOS-Stade was also invited to join the group to better address alumina value chain topics and further maximize the potential impact. This Task Force provides valuable contributions on policy and advocacy topics, particularly regarding the analysis of legislative obstacles at the European level that may impede the implementation of the most optimized sustainable solutions for BR valorization. Additionally, it focuses on developing harmonized consolidated industry recommendations and supporting various events by providing views and suggestions. It is noted, this TF meets online regularly, at least twice per year.

4.1.2 Policy & Standardization Working Group

Within the framework of the EU ReActiv project, European Aluminum established a "Policy & Standardization Working Group (WG)." This WG, coordinated by European Aluminum, includes members from Holcim, Metlen Energy & Metals, HOP3, Clausthal University of Technology, KU Leuven, and the IAI. It was launched in November 2023. Its primary focus is on supporting the European standardization of cements containing BR as a new constituent, analyzing the legislative specificities of alumina and cement plants in Europe, and consolidating industrial recommendations regarding the requested EN standards and EU policies to enable the full deployment of ReActiv processes across Europe.

4.2 Increasing Awareness About Optimized Solutions for BR Valorization

To share insights into the key advancements of RemovAL and ReActiv and identify regulatory barriers to deploying relevant innovations, European Aluminum's Innovation Hub has organized policy and cross-fertilization workshops. To date, four workshops have been held focusing on presenting the innovative processing routes developed under these projects to unlock the added value of BR (Table 5). These events addressed technological and non-technological enablers for the successful implementation of these innovations.

Table 5. Workshops organized by European Aluminum in the frame of RemovAL and ReActiv.

Project	Title	Date & Place	Type
RemovAL	"Towards an EU regulatory framework boosting use of slags and residues of the metal sector"	6 Nov 2019, Brussels, BE	Policy
RemovAL/ ReActiv	"Towards a more sustainable alumina production in Europe"	23-24 Sep 2021, online	Cross-fertilization
ReActiv	"Boosting circularity in the process industry: Focus on industrial symbiosis between the aluminum and cement sectors"	26 Sep 2022, online	Cross-fertilization
RemovAL	"Turning residues of the aluminum industry into resources"	10 Oct 2022, Athens, GR (hybrid)	Cross-fertilization

These workshops brought together researchers, industry experts, and stakeholders from various sectors worldwide to share knowledge and best practices (Figure 5). By showcasing innovative approaches developed within these projects, the workshops aim to inspire collaboration and the exchange of ideas. This collaborative environment was designed to identify common goals, promote interdisciplinary partnerships, and explore opportunities for future initiatives that can enhance the impact of ongoing and future projects.

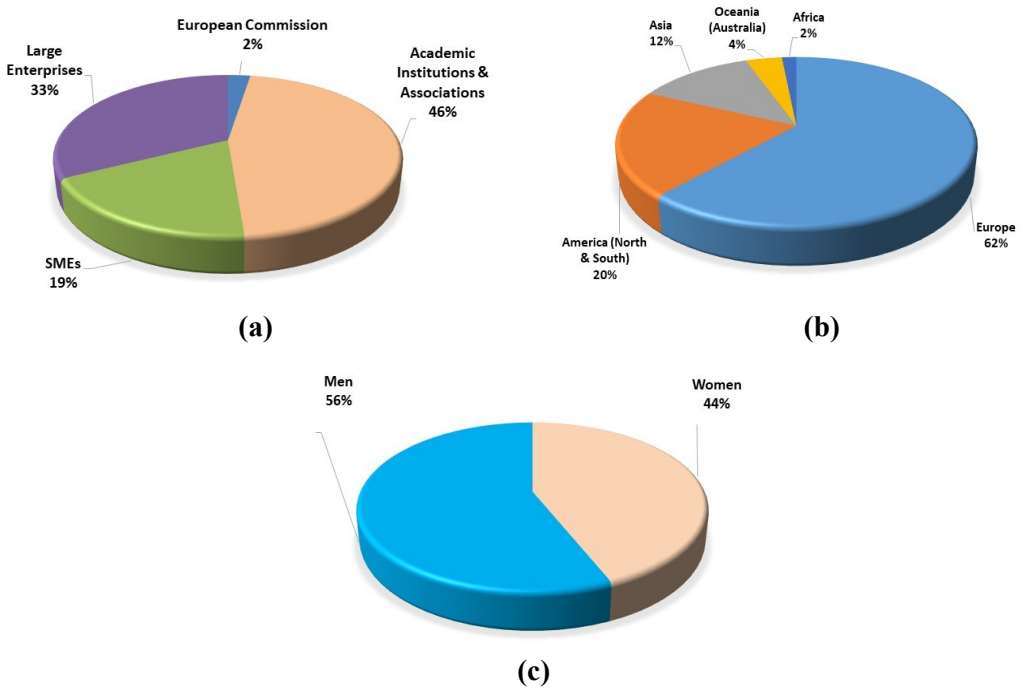

Figure 5. Distribution of experts by (a) type of organization, (b) geography and (c) gender.

4.3 Contributing to EU Policy Initiatives

The Joint Research Centre and the Directorate-General for the Environment conducted the Science for Policy research study titled "Scoping possible further EU-wide end-of-waste and by-product criteria" [12] to assist the Commission in implementing both the Circular Economy Action Plan and the Waste Framework Directive. The study aimed to:

- identify a list of priority waste or by-product streams for which to develop further EU-wide end-of-waste or by-product criteria (scoping).

- derive a shortlist of top-candidate streams for which to develop further EU-wide end-of-waste or by-product criteria.

As a result of previous consultations, various stakeholders suggested several waste and by-product categories, such as BR, biomaterials not covered by the fertilizing products regulation, synthetic gypsum, mill scale, mineral fractions of construction and demolition waste, paper and cardboard, plastics, rubber, slags (ferrous and non-ferrous), textiles, and waste electrical and electronic equipment. These categories were considered candidates for the development of further EU-wide end-of-waste or by-product criteria.

Within the framework of this study, European Aluminum initiated a consolidation process and prepared a final document highlighting the benefits of classifying BR as non-waste/by-product. This was supported by key case-studies and stressed the need for proper adaptation of legislation and harmonized criteria, based on feedback and support from its Alumina Membership. It is explicitly mentioned that such action would enhance further market acceptance of BR and boost the concept of novel industrial symbiotic value chains and resource efficiency in Europe.

Based on the final ranking of the candidate streams (see Figure 2, p.88 of the JRC/DG ENV study [12]), BR was not considered in this priority list due to the mineralogical and chemical composition variability of BR generated from different alumina refineries, as well as the possible risk of metals and metalloids leaching. Additionally, the development of EU-wide end-of-waste or by-product criteria for BR was strongly supported by industry representative (i.e., European Aluminum), but it was reported as a non-priority stream by one or more Member State representatives. European Aluminum intends to continue emphasizing the need for including BR in the priority list of harmonized criteria in future rounds to enable the proper valorization of BR within the broader concept of a circular economy.

4.4 Supporting the Development of the RemovAL Industry Recommendations for the Policy Makers

Building on the advancements of the EU RemovAL project, European Aluminum, with support from alumina producers, has identified key industry recommendations to further facilitate the deployment of optimized solutions for the valorization of BR from operating plants and legacy sites. The first two recommendations are directly connected to the legislative framework, while the remaining six pertain to the policy and societal framework enabling BR valorization:

- Defining EU harmonized End-of-Waste criteria for processed BR from operating plants and legacy sites should facilitate the deployment of relevant innovation.

- The registration of BR under REACH would increase the market acceptance of BR and BR-based products. The Innovation Hub together with the alumina producers from the membership are exploring all options towards such registration [2].

- Incentives should be provided for the use of BR and/or other industrial by-products over virgin raw materials.

- Efforts should be made to increase awareness and social acceptance among end-users regarding the valorization of BR.

- The role of Public-Private Partnerships in fostering synergies between academia, industry, and society should be reinforced.

- Industrial symbiosis should be further enabled though improved knowledge and expertise.

- The environmental benefits of RemovAL BR valorization pathways should be further reinforced through the decarbonization of the energy sector.

- Better synergies between the Horizon Europe program and the Innovation Fund framework should boost innovation for circular economy projects in the process industry sector.

New industry recommendations are expected to be developed from the EU ReActiv project with an emphasis on advancing the value chain of BR-based SCMs towards the market.

5. Conclusions

As European alumina refineries actively seek innovative and cost-effective processing routes to transform the challenge of BR management into an opportunity, adhering to the EU's circular economy principles, cross-sectoral collaboration becomes crucial. European Aluminum's Innovation Hub plays a key role in promoting such collaboration and driving innovation within

the aluminum industry. By engaging with key stakeholders, organizing policy and cross-fertilization workshops, and contributing to EU policy initiatives with the support of the alumina producers from the Membership, the Innovation Hub unites diverse stakeholders, facilitating the exchange of insights, exploration of novel technologies, and investigation of comprehensive valorization pathways. This collaborative effort not only addresses immediate challenges but also significantly enhances the long-term competitiveness, sustainability, and resource efficiency of the European aluminum sector.

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