Could “red mud” be the answer to some of Europe’s critical-metal supply concerns?

The answers to the current raw-material supply challenges being faced by Europe lie in technological innovations that increase the efficiency of resource utilization and allow the exploitation of yet untapped resources, such as industrial waste streams and metallurgical by-products. One of the key industrial residues that is currently not or only poorly valorised is bauxite residue (BR, more commonly known as “red mud”) from alumina refineries.

In 2016 the European alumina and primary-aluminium industries utilized about 12 million tonnes of bauxite to produce about 7 million tons of alumina (out of the 115 million tonnes produced worldwide), and imported an additional 4 million tonnes of alumina to produce about 4 million tonnes of primary aluminium (out of the 59 million tonnes produced worldwide).

A number of processes have been proposed, but never implemented, for the simultaneous recovery of the major metals from bauxite residue (towards “zero waste” objective). Despite the lab-scale success of much of the work so far the industrial utilization of BR is estimated at just 2.4 million tonnes, accounting for less than 2.5% of the annual BR production.

The main barriers to applying any solution for the valorisation of BR are the techno-economic viability of the solution and the legislative environment. To change this, environmental policy actions are needed, to provide incentives for industrial symbiosis and simplify the waste-transfer or waste de-characterisation process across Europe.
Bauxite Residue Worldwide

Bauxite residue (BR) is produced as a red slurry (hence the common term “red mud”) and contains iron minerals and other non-alumina-bearing bauxite minerals, as well as the liquor desilication product (calcium and sodium alumino-silicate precipitates) from the Bayer process cycle. It is estimated that for each tonne of alumina produced, 0.9-1.5 tonnes of solid residue are generated, depending on the initial bauxite-ore grade and the alumina’s extraction efficiency. As the global demand for aluminium metal increases, so does BR production, currently in excess of 150 million tons per year, worldwide. This BR is generated at some 60 active Bayer plants. In addition, there are at least another 50 closed legacy sites, so the combined stockpile of bauxite residue at the active and legacy sites is estimated at 3-4 billion tonnes.

The management and storage of bauxite residue have evolved over the decades. In the early Bayer alumina plants, the residue was often just stockpiled close to the site or in a nearby depleted bauxite/shale/coal mine or quarry sites. Later, as the nearby areas were filled, valleys were dammed to contain the ever-growing volume of residue. Prior to 1980, most of the inventory of BR was stored in lagoon-type impoundments and the practice continues at some facilities.

As the land for lagoon storage became scarce for many plants, “dry stacking” methods were adopted. These dry-stacking regimes were first adopted in the 1940s, and since the 1980s the trend has been increasingly towards dry stacking in order to reduce the potential for the leakage of caustic liquor to the surrounding environment, reduce the land area required, and maximise the recoveries of soda and alumina. Dry stacking is now the most common method adopted at large alumina refineries.

Filtration using drum filters and plate and frame filter presses to recover caustic soda, reduce moisture levels and realise more handle-able bauxite residue has been employed for some 80 years, and is now becoming more popular. In addition to recovering more caustic materials, this technique provides considerable benefits in terms of reuse as the material is normally produced as a friable cake, with typically less than 28% moisture, and a lower soda content, thereby dramatically reducing transport issues and costs.

Filter-pressed (dry) bauxite residue being stockpiled in Greece, at Mytilineos S.A. (former Aluminum of Greece)

The Auginish (RUSAL) alumina refinery in Ireland. The blue area is the space allocated to the refinery; the red is the the bauxite-residue disposal area.
The large volume of waste produced during the Bayer process has been of concern to alumina producers since the early days of its adoption. In cases where land availability is becoming limited, the ever-growing demand for BR disposal space, ultimately threatens the longevity of established alumina refineries. BR disposal in the alumina refinery in Greece takes up 1 km² of land for an annual 0.75 mtonne BR deposit. At the Auginish plant in Ireland, the management of the 1.2 mtonne of BR produced annually results in the current land use of 1.83 km². Stopping BR disposal or gradually reclaiming the legacy BR disposal sites is vital for both industry and society.

The list of areas where bauxite residue could be used covers almost all areas of inorganic material science, with a particular focus on the recovery of elements present in the bauxite residue. Even Bayer himself, in his 1892 patent, describing the Bayer Process, proposed the potential for iron recovery. Seeking effective solutions has attracted many researchers from industry, universities, institutes, and entrepreneurs to develop applications including cement, bricks, roads, etc., soil remediation, as well as base metals and critical raw-material (CRM) metallurgical extraction. This vast majority of research and studies on BR utilisation is demonstrated by the more than 700 patents since 1964. The possible applications can be broadly broken down into these categories:

- recovery of specific elements present in the bauxite residue, e.g., iron, titanium, aluminium, rare-earth elements (i.e., lanthanides, yttrium and scandium);
- use as a major component in the manufacture of another product, e.g., cement;
- use of the bauxite residue as a constituent in a building or construction material, e.g., road building, dyke construction, concrete, tiles, bricks, mineral-wool insulation;
- use for some specific property that might include the conversion of the bauxite residue to a useful material by modifying the compounds present, e.g., catalysis, phosphate trapping, soil
amelioration, landfill capping, acid mine drainage treatment.

A number of processes have been proposed, but never implemented, for the simultaneous recovery of the major metals from bauxite residue (towards the “zero-waste” objective). Concerning cost and risk, a detailed cost/benefit analysis, of one or more specific process proposals, is needed, not only to establish economic viability, but also to deal with the whole volume of the produced residue. Despite the lab-scale success of much of the work, so far industrial BR utilization is estimated at 2-4 million tonnes, accounting for less than 2.5% of the annual BR production, with the main applications in the construction sector and iron-steel production.

In 2016 the European (EU28+EFTA) alumina and primary-aluminium industries utilized about 12 million tonnes of bauxite to produce about 7 million tons of alumina (out of the 115 million tonnes worldwide), and imported an additional 4 million tonnes of alumina to produce about 4 million tonnes of primary aluminium (out of the 59 million tonnes worldwide). The alumina and primary-aluminium sector in Europe directly employs about 16,000 people. This sector is the basis for the whole European aluminium industry, which employs directly and indirectly more than 1,000,000 people at more than 600 plants and generates about €40 billion in annual turnover (source EA). This sector is associated with two by-products that undermine its sustainability: BR from alumina production and Spent Pot Lining (SPL) from primary aluminium production.

In Europe, alumina refineries operate in Bosnia & Herzegovina, France, Hungary, Germany, Greece, Ireland (AAL), Romania (ALUM), Spain and Ukraine, while significant BR deposits from refineries that have stopped their operations (legacy sites) exist in Italy, France (RT), Germany, Hungary and other countries. The current BR production level in the EU is 6.8 million tonnes per year; while the cumulative stock-piled level is a staggering >250 million tonnes (dry matter). The catastrophic red-mud dam failure at the Hungarian Ajka refinery in 2010 is indicative of the magnitude of the residue-disposal challenge and its high environmental and economic impact.

Although numerous sporadic projects and isolated research efforts have attempted to utilize BR as a feedstock in other sectors (cement, iron, etc), clear-cut cases of industrial utilization of BR
are rare and can only be applied on a fraction of the produced BR in a refinery. Globally, BR as an iron (or alumina) source in clinker cement production is perhaps the most widespread BR utilization, varying between 2 and 4 million tonnes per year worldwide (mostly in China and India). This represents less than 3% of BR global production, as this practice is challenged by various factors ranging from transport costs and logistics, to limitations imposed by process chemistry, leading effectively to small amounts of BR in the raw meal of the clinker. Out of the 6.8 million tonnes of BR produced annually in Europe, only 10 thousand tonnes are re-used in Greece as a raw material for clinker cement. However, despite more than 50 years of research and many publications and patents, the widespread, high-added-value use of BR has not taken place. This is due to several barriers that hamper its effective exploitation such as:

- **Volume:** Applications that consume large quantities of residue are required.
- **Performance:** The performance of the residue in any application must be competitive with the alternatives in relation to quality, cost and risk.
- **Costs:** No strong economic case has yet been established. Technical propositions need to come with a justifiable economic analysis that demonstrates viability.
- **Risk:** It must be proved to industry

### European Alumina and BR production

<table>
<thead>
<tr>
<th>Country</th>
<th>Location</th>
<th>Total Alumina Annual Capacity (kt) (source EA)</th>
<th>Estimated BR (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greece (AoG)</td>
<td>Viotia</td>
<td>850</td>
<td>750</td>
</tr>
<tr>
<td>Ireland (AAL-RUSAL)</td>
<td>Aughinish</td>
<td>1,990</td>
<td>1,800</td>
</tr>
<tr>
<td>Romania (ALUM)</td>
<td>Tulcea</td>
<td>500</td>
<td>450</td>
</tr>
<tr>
<td>France (ALTEO)</td>
<td>Gardanne</td>
<td>635</td>
<td>570</td>
</tr>
<tr>
<td>Germany (AOS)</td>
<td>Stade</td>
<td>1,050</td>
<td>950</td>
</tr>
<tr>
<td>Spain (ALCOA)</td>
<td>San Ciprian</td>
<td>1,500</td>
<td>1,350</td>
</tr>
<tr>
<td>Turkey</td>
<td>Seydisehir</td>
<td>490</td>
<td>440</td>
</tr>
<tr>
<td>Bosnia &amp; Herzegovina</td>
<td>Birac</td>
<td>600</td>
<td>540</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>7,615</td>
<td>6,850</td>
</tr>
</tbody>
</table>

### Recent European projects on BR reuse

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Funding/Coordinator</th>
<th>Related Technology</th>
<th>Finishing TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN EX AL</td>
<td>FP7/2010-2014 Coord. Aluminum of Greece (Mytilineos S.A)</td>
<td>Production of pig iron and mineral wool from BR in Electric Arc Furnace</td>
<td>7</td>
</tr>
<tr>
<td>EU Rare</td>
<td>FP7/2013-2017 Coord. NTUA</td>
<td>Leaching of REE from BR</td>
<td>5</td>
</tr>
<tr>
<td>SCALE</td>
<td>H2O20/2016-2020 Coordinator AoG</td>
<td>Pilot plant for scandium extraction from Greek BR</td>
<td>7</td>
</tr>
<tr>
<td>RECOVER</td>
<td>KIC/2017-2020 Coordinator KUL</td>
<td>Pilot plant for Inorganic polymer products from BR</td>
<td>6</td>
</tr>
<tr>
<td>Eyde Waste 2 Value</td>
<td>National Project Norway/2016-2019 Coord. ELKEM</td>
<td>Production of iron alloy from different waste streams including Spent Pot-Lining (SPL)</td>
<td>6</td>
</tr>
</tbody>
</table>
that the associated risk in any application is less than the risk associated with continued storage.

Technologically, BR reuse solutions can be found as stand-alone in the literature, but pooling them together and optimizing them in an integrated manner is the only way to render bauxite residue reuse viable from an economic point of view and acceptable for industry. It is thus necessary to combine more than one technology in order to achieve viable and meaningful BR utilization.

The financial viability of such an approach has been published at a conceptual level by AoG, based on RTD experience. In the table (below) and graph (next page), a scenario combing EAF processing for iron production, hydrometallurgical leaching for REE/Sc and slag valorisation for cement, inorganic polymers and mineral wool is examined. The end-product value in each case is strongly dependent on integrated processing and innovation, i.e., the difference between producing Fe-Si instead of pig-iron or a pure Sc$_2$O$_3$ concentrate instead of mixed REE/Sc concentrate. The scenario developed assumes the processing of the entire annual BR production of AoG (i.e., 700,000 tonnes) and presents the total low and high revenue to be achieved against an averaged and simplified OPEX. Similar techno-economic assessments for a holistic BR treatment flow sheet have been published by other groups.

**Bauxite residue as resource in Europe**

Bauxite Residue from the alumina industry is stockpiled at a rate of 7 million tonnes on a dry basis per year in Europe:

- With an average iron oxide content of 40 wt%, it can be considered as an equivalent of 3.4 million tonnes of iron ore available in Europe. This results in a 4% decrease in iron-ore imports and a 18% increase in Euro-
Examples of holistic BR processing concepts, based on the mud2metal flowsheet, described in the table on the previous page.

### Main barriers to industrializing BR recycling solutions

The alumina industry identifies, as the main barriers to applying any solution for the valorisation of BR, not only the techno-economic viability of the solution, but also the legislative environment for applying the solution. The simplest BR recycling option, utilization in cement clinker raw meal, is hindered by the European waste legislation that dictates that the cement company receiving the BR has the appropriate licence that allows it to utilize/process wastes in its operations. When the company is in a different country from the alumina refinery, a specialized transfer procedure is needed. And while most cement plants have licences to process waste materials, the same is not true for other sectors (iron industry, building materials, etc), which could implement novel BR reuse solutions.

In sending BR to another industry for valorisation, an EU alumina refinery today must face:
• costs for licensing the transfer and the cost of the transfer itself (more so across boarders)
• potential gate fees at the end-user industry, a practice that is very common, effectively negating the premise of a circular economy.
The alternative, i.e., to landfill the BR, is often not only the more economical solution but also a far less complicated solution.

To lift such barriers two main policy actions are identified:

1. Simplify the de-characterization process for BR (especially when it is delivered as material with less than 30% moisture) from waste to by-product or raw material. This would greatly simplify both the transport and the reuse of BR in other industries, driving down costs and time. The legislative framework for this already exists in many countries, as a non-hazardous waste can be de-characterised if the appropriate conditions exist; such as: there is a use for the waste in other process, that the use of the waste does not pose a threat to human health and others. However, such de-characterisation decisions are very difficult to be reached independently by national governments, as such issues are very sensitive for the public. A related EC wide directive/policy on de-characterization of BR is needed.

2. Provide incentives to industries for prioritizing the use of industrial by-products over virgin raw materials. Currently, industries that could utilize BR as iron and alumina sources in their process have no incentive to do so, as virgin raw materials are cheap and their use less complicated. Companies would only use BR if it comes at a lower price or even at negative price (gate fees). The EU needs to provide economic and social incentives to industries that promote circular-economy practices, otherwise by-products like BR will only be utilized where and when virgin raw materials are scarce or depleted. Incentives could have the form of tax reductions, CO2 emission allowances, and greene-product labels.

Want to react? Send your comments to efthymios.balomenos-external@alhellas.gr
To tackle its critical raw-material dependency, Europe needs comprehensive strategies based on sustainable primary mining, substitution and recycling. Freshly produced flows and stocks of landfilled industrial residues such as mine tailings, non-ferrous slag and bauxite residue (BR) can provide large amounts of critical metals and, concurrently, minerals for low-carbon building materials. The European Training Network for Zero-Waste Valorisation of Bauxite Residue (REDMUD) therefore targets the vast streams of new and stockpiled BR in the EU28. BR contains several critical metals, is associated with a substantial management cost, whereas spills have led to major environmental incidents, including the Ajka disaster in Hungary. To date, the zero-waste valorisation of BR is not happening. The creation of a zero-waste BR valorisation industry in Europe urgently requires skilled scientists and engineers, who can tackle the barriers to develop fully-closed-loop environmentally friendly recovery flow sheets. REDMUD trains 15 researchers in the S/T of bauxite-residue valorisation, with the emphasis on the recovery of Fe, Al, Ti and rare earths (incl. Sc) while valorising the residuals into building materials. An intersectoral and interdisciplinary collaboration of EU-leading institutes and scientists has been established, which covers the full value chain, from BR to recovered metals and new building materials. Research challenges include the development of efficient extraction of Fe, Al, Ti and rare earths (incl. Sc) from distinct (NORM classified) BRs and the preparation of new building materials with higher than usual Fe contents. By training the researchers in pyro-, hydro- and ionometallurgy, electrolysis, rare-earth extraction and separation technology, inorganic polymer and cement chemistry, lifecycle assessment (LCA), NORM aspects and characterisation, they become the much needed scientists and engineers for the growing European critical-raw-materials industry.

Key project information:
Project type: H2020 MSCA-ETN (01/12/2014 to 31/10/2019)
Website: http://etn.redmud.org
EU contribution: €3.72 m
Coordination: KU Leuven

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