Green Alumina a Technological Roadmap

Alessio Scarsella[1] and Edgar Gasafi[2]
1. Director Light Metals
2. Senior Product Manager
Metso Outotec GmbH, Oberursel, Germany
Corresponding author: alessio.scarsella@mogroup.com

Abstract

The Green Aluminium phenomena although recent in notion, has been materializing over the last century with the first dedicated hydroelectric power stations for Aluminium production being commissioned early in the 20th century. With the EU emission target strategy in full swing, individual producers setting their own values and speculation on the formation of a newly indexed metal, producers, technology suppliers and regulators are trying to common ground to materialize a niche portion of Aluminium production to meet the emission related targets. The carbon dioxide makeup of Aluminium production is dominated by the electrolytic reaction followed by the anode consumption and then the Bayer process. Industry has spent significant efforts in decarbonizing the former two, the later still needing strong conceptual development. This paper intends to explain the conceptual contribution towards Green Aluminium from the perspective of a Bayer process technology supplier.

Keywords: Aluminium, Alumina, Green, Renewable Energy, Zero Carbon.

1. Introduction

The Paris Agreement is a **legally binding international treaty on climate change adopted by 190 countries with the clear intent to combat climate change.** In the United States approximately 46% of carbon dioxide emissions are generated through manufacturing processes or electricity production [1], the latter constituting the majority of emissions (approx. 67 %). Aluminium production is an important emissions contributor and has often been denoted as “Congealed Energy”. The actual amount of electricity (Figure 1) dedicated to the primary Aluminium production process is relatively small when compared to overall electrical energy production, however Aluminium production still generates 760 million tonnes of carbon dioxide every year, also considering that 15% of world Aluminium production is generated by renewable means (IEA, 2020) [2].

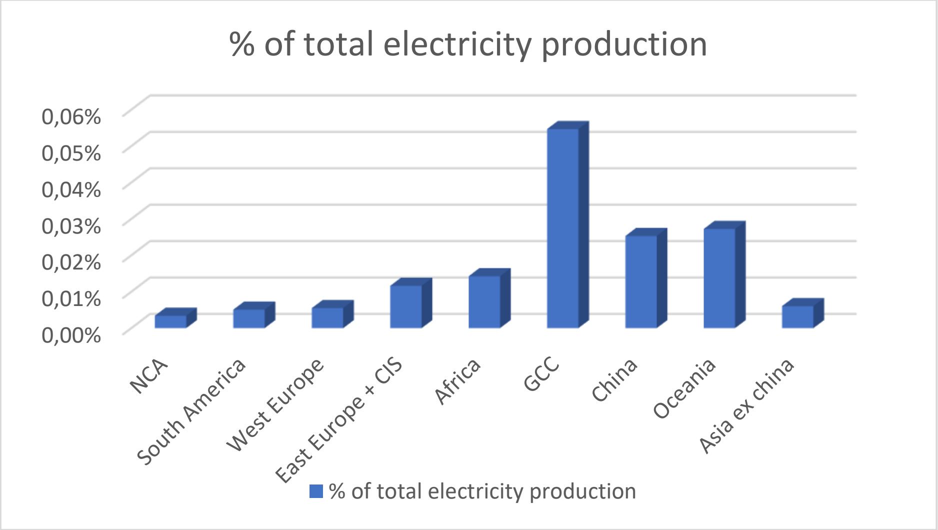

Figure 1. Percentage of total electricity production directed to aluminum smelting by region (note only Aluminium producing countries were taken into consideration, IEA 2020).

In recent years a series of primary Aluminium producers have flagged their intent to produce and market low carbon Aluminium with a specific carbon dioxide footprint of 4 tonnes of carbon dioxide per tonne of Aluminium. To complement these initiatives the European commission is proposing a carbon border adjustment mechanism, where the EU will start to equalize the price between domestic primary produced Aluminum against low carbon imports (European Carbon Border Commission, 2021). Arguably this trend is compounded by trading houses to facilitate the indexation of this new product separately. Considering that the Aluminium consumption in Europe is approximately 15- 20 % of total production (European Aluminium Association, 2019), this combination of initiatives certainly pushes producers and technology providers to achieve a new benchmark in Best operating or Best engineering practice.

2. The Carbon Footprint of Aluminium Production

The wide acceptance of the Bayer process and Hall-Heroult processes as being the benchmark for primary Aluminum production is a given. These process routes have received the majority of attention from an R&D, product management and engineering perspective and moving forward in the future, this is unlikely to change. The primary Aluminium production carbon footprint typically oscillates between 12-20 tonnes of carbon dioxide per tonne of Aluminium metal, the majority of this comes from the endothermic reduction process, followed by anode consumption and then the Bayer process. Major industry players have already invested in powering Aluminium reduction by renewable means (mainly hydroelectricity). The difference on the carbon makeup between Aluminium reduction fueled by non-renewable means versus renewable means is highlighted in Figure 2.

The technological advances of inert anodes such as the Elysis based partnership between Rio Tinto and Alcoa [5] and UC Rusal's own development [7] is slowly turning into a full-scale commercial rollout followed by a new benchmark in technology for the primary Aluminium smelting process. The full-scale implementation of renewable energy into primary Aluminum production coupled with inert anode technology could definitively mean an Aluminium carbon footprint of 2.5 tonnes of carbon dioxide per tonne of Aluminium is realistic, which largely leaves the Bayer process itself as the last node to untwine, and although a "*Zero Carbon Aluminum billet*" maybe stretching reality, however a significant reduction in the carbon footprint is definitely within reach.

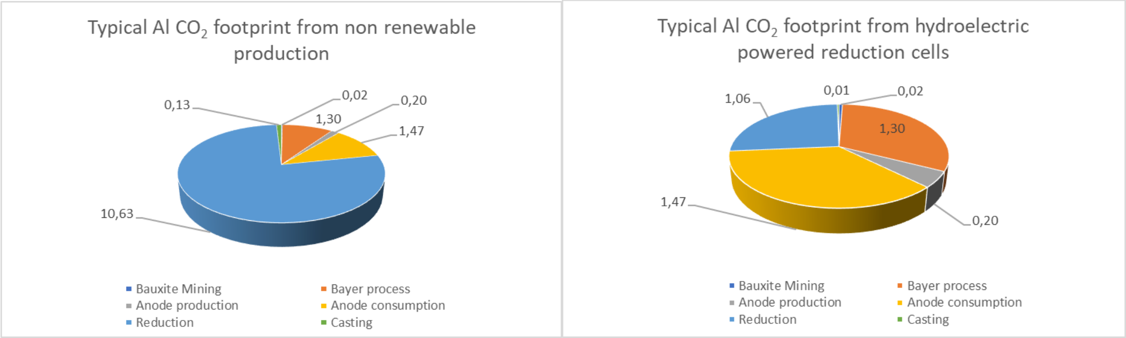

Figure 2. Primary Aluminium production carbon dioxide footprint.

3. The Road Towards Renewable Aluminium Production

Much like the reduction process the Bayer process is also heavily reliant on energy, however unlike the reduction process the direct application of electrical power sources make the implementation of renewable energy challenging. In order to decipher industry needs and in order to make alumina production green some key definitions need to be proposed followed by a unit-by-unit breakdown of the Bayer process and include the following:

The source:

An energy source is self-explanatory, currently the majority of alumina refineries worldwide rely on natural gas, coal, coal gas or heavy fuel oil. When referring to low carbon energy sources, examples that can be taken into consideration such as hydroelectric, nuclear, wind, solar etc. However, the application of each of these in either brownfield or greenfield refineries is extremely subjective with a multitude of inputs required for a fit for purpose solution.

The conduit:

The conduit can be reasonably defined as the means or method of transportation of energy to an energy sink. Since the Bayer process is a mixture of a hydrometallurgical and pyrometallurgical process, today these conduits consist of electricity, steam, natural gas, gasified coal or heavy fuel oil with the latter three addressing the pyrometallurgical section of Bayer process. In a low carbon context, the nature of the conduit becomes equally as important as the source, these would naturally include steam and electricity, but also Hydrogen, molten salt and heating oil(s).

The sink:

In the Bayer process there generally are three main energy sinks:

1) Hydrometallurgical sinks, which are basically steam consumers of which the biggest are digestion and evaporation, followed by other minor consumers consisting of pre-desilication, residue settling circuit and hydrate filtration etc.
2) Electrical sinks; consisting of blowers, pumps, electrostatic static particles (ESP), mills etc.
3) Pyrometallurgical sinks, which is basically the Alumina calciner.

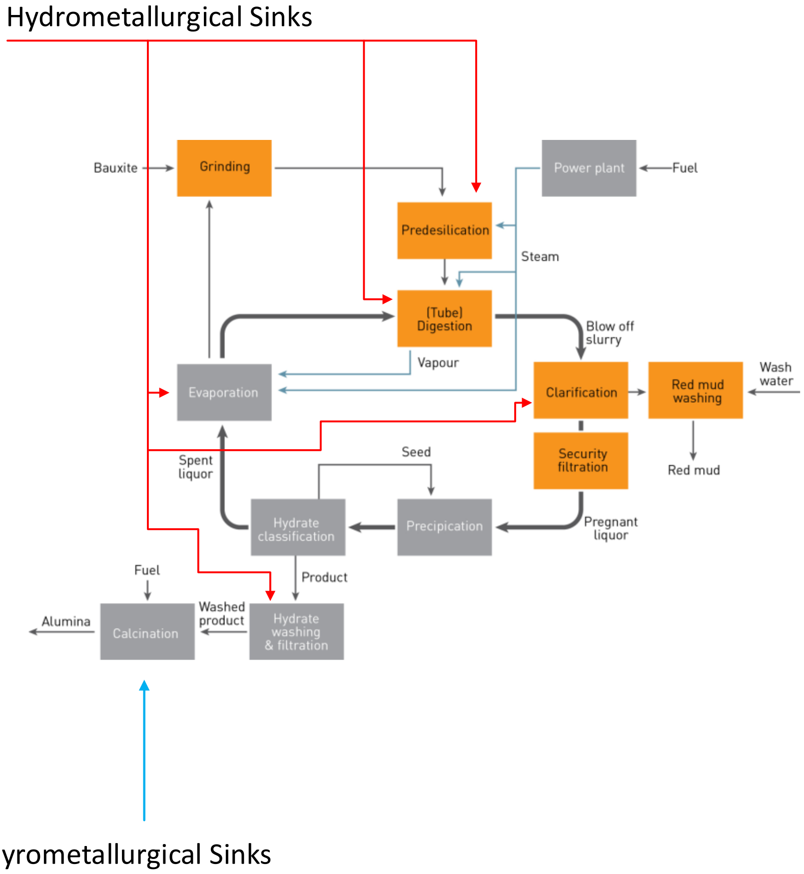

Figure 3. Hydrometallurgical and pyrometallurgical sinks in the Alumina Refinery.

4. The role of the Technology Supplier

4.1 The Source

There is a wide array of technologies with differing maturities making their way to the market. The main focus is towards electricity generation however, this does not mean that altering versions can be made to accommodate other types of conduits such as heat carriers. It is not the intention of the author to expand on this topic in this manuscript, however these can include for example: solar concentrators with heliostats, photovoltaic cells, hydroelectric, tidal, geothermal or wind.

4.2 The Conduit

The conduit is an extremely sensitive topic, already mentioned; electricity, hydrogen, steam and heating media are clear examples, however the quantities required in an economically feasible scenario for Alumina production are high, that in turn would mean that technology providers of the conduit need to accommodate with scaled designs. The following concepts could in practice be considered for Alumina production:

- Electrically raised steam.
- Electrical conversion into thermal energy storage of heating media such as molten salt or heating oil.
- Direct electric use in the refinery.

Electrically raised steam

Use of electrical energy for the purpose of raising steam has been common in a wide range of applications, such as the pharmaceutical and marine sector.

Electrically driven steam boilers are simple thermistor-based devices, where current is passed through a resistor element, heat generated and steam generated through direct contact. This technology has been around for a relatively long time. However, they produce modest amounts of steam far from that required for Bayer process applications. These boilers are typically fed by 300 – 700 Volt lines and are delivered as units skids of up to 5 MW.

Electrode boilers operate differently, also a mature technology these use boiler water as the resistive medium by passing high voltage current (6 – 24 kV), causing water to immediately vaporize (see Figure 4). The availability of industrially sized units on the market are common (Figure 5), to the point that scalability may not necessarily be a concern for meeting the steam requirements for Bayer process operation.

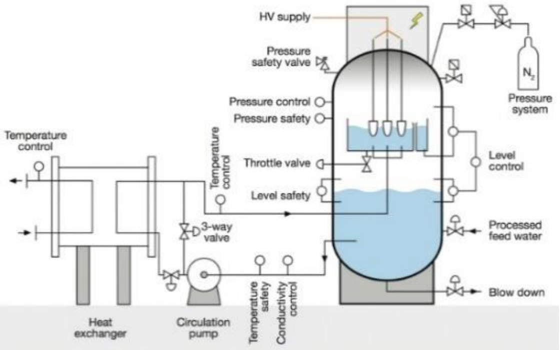

Figure 4. Schematic of an electrode-based boiler (Modern Power Systems, 2018).

Figure 5. 10 MW district heating facility in Milan, Italy (Modern Power Systems, 2018).

Table 1. Examples of electric steam boiler technology.

Vendor	Max Pressure, Bar	Max Tonnage, t/h	Technology
Chromalox	16	0,25	Indirect
ABCo	190	1,5	Indirect
Ecotherm	8	2	Indirect
RF Macdonald	34	150	Electrode
Parat	85	90	Electrode

Electrical conversion into thermal energy storage such as molten salt or heating oil

Heating media have been used in the Aluminium value chain for some time, mainly in the production of anodes, but also as a heating agent for digestion (Scarsella *et al*., 2012 and Scarsella *et al*., 2015). Fossil fuel fired molten salt and heating oil-based heaters vary with a wide range of duties, however when it comes to electrically driven units their respective duties are in comparison small, far too low to reasonably accommodate the thermal requirements of an alumina refinery. With the current status of products on the market the number of electrically driven heating media units would most certainly render Alumina refinery project establishment uneconomical.

Table 2. Examples of electric heating technology.

Vendor	Media	Duty, MW
HeatLL	Oil	1,6
Hangzhou Wansen	Molten salt	0,65
Jiangsu	Oil	1,4
Riyuan Chromalox	Oil	0,3
BBS	Oil	16
HTT	Oil	4

Direct electrical energy use in the refinery

Direct use of electricity in the refinery becomes challenging with available of "*go to market*" solutions far and few. Alumina refinery energy is mostly consumed in the heating up of process liquor in digestion and evaporation and in the heating up of combustion air in the calciner and the endothermic calcination reaction itself.

The direct use of electrical energy used to heat up process liquor in theory would be an attractive option, thyristor type electrical heat exchangers or emersed heaters would be of important use. However, often thyristor-based heating elements have very acute thermal gradients and would attract scale formation, which is commonly associated with Bayer Liquors and a known problem throughout the industry. Frequent chemical and mechanical attention for an electrical solution would be required, and a corresponding design coupled with an appropriate operational and maintenance philosophy would need to be in place in order to ensure the high operating factor demanded by the Bayer process.

Induced plasma flames (or electric arc) have found their way to the large-scale smelting of copper concentrates, they operate by sending a high voltage arc through a high velocity gas, in some cases reaching temperatures greater than 9000 °C. Such temperatures have little practical applicability in terms of direct liquor heating, however, a high temperature gas could be used to pre heat combustion air or even drive the calcination process in its entirety.

Figure 6. Metso Outotec submerged arc furnace.

4.3 The Sink

It is the Author's belief that this is the area which requires the most attention, as the development times would depend on the maturity of the solution. As already highlighted in section 3 there are essentially three types of sinks considered in Alumina production, these are the hydrometallurgical sinks which are traditionally fed by superheated steam (Digestion and Evaporation above all), pyrometallurgical sinks which essentially is the calcination process and electrical sinks which are direct electrical consumers. This paper will purposefully expand on the first two items.

Hydrometallurgical sinks

Understanding the hydrometallurgical energy sinks requires some basic understanding of the Bayer process and in particular digestion and evaporation. Progressive efforts have been made to reduce the thermal footprint of the Bayer process units with reasonable success (Scarsella *et al*., 2015). However, the question does remain how to directly introduce a low carbon energy source from one of the above specified conduits. Since both Digestion and Evaporation are traditionally powered by steam than the answer is self-explanatory, however there are still significant losses in steam associated with Digestion blow off not to mention scope to introduce more low carbon energy into evaporation.

A modern 2 Million tonne per annum alumina refinery would lose about 40 to 100 t/h of steam as blow off in digestion. Typically, this blow off steam may contain some fine caustic mist deriving from the main process, Blowoff steam constitutes a non-negligible energy loss, substantial efforts have been made over the last 40 years to minimize this via different digestion designs (Scarsella *et al*., 2012), and one topic that merits further exploration is the recompression of blow off steam for further reuse in the refinery.

Vapor recompression in evaporation proposes an attractive low carbon solution, however in this case it is a proven technology that can artificially increase steam pressure and thus its enthalpy for re-use. Vapor recompression does not decrease necessarily the energy sink, but it does yield the opportunity to introduce a low carbon energy source from one of the conduits mentioned in section 4.2. Two generic technologies for vapor recompression are widely used throughout the chemical, process and metallurgical industries:

1) Steam ejectors using high pressure steam as a motive source
2) Mechanical vapor recompression of process vapor (at any point of the unit operation)

Steam ejectors offer a low cost mechanical solution but have limitations on thermal efficiency due to the required compression ratio of the suction fluid there is a need of a high pressure motive fluid thus bringing additional infrastructure to the solution. Improvement of the enthalpy of digestion blow off steam or evaporation flash steam would mean multiple recompression stations in series and parallel lines to meet efficiency and shear volume demands and reticulation of high pressure piping make it an unfavorable design decision.

Mechanical vapor recompression, conversely, can be achieved via a centrifugal blower. Typically, a single blower could reduce the energy consumption of single evaporation battery by 2-5%. Likewise, in digestion four centrifugal blowers could turn approximately 40 t/h of blow off steam from a modern tube digester into a meaningful source of reusable energy.

Pyrometallurgical sinks

Naturally the pyrometallurgical sink associated with the Bayer process revolves around the calcination step, this can be essentially dissected into three separate facets, drying of hydrate, heating of combustion air and hydrate, and the endothermic reaction of the calcination reaction itself. Concepts on how to bring renewable energy via electricity into the calcination process have been conceptually studied such as electrical combustion air pre-heaters or an electrically driven bed hydrate dryer. The constant “risk vs reward” status being challenged under competitive market conditions has essentially deterred technology suppliers from making definitive technical inclusions.

As mentioned in section 4.3, the direct application of electricity in the calcination process could also mean the use of plasma technology to heat sufficient air to drive the drying and calcination reaction, however there are some technical risks associated with applying high temperature media for the purpose of calcining which needs to be solved; such as the effect of corundum formation, thermal breakage of hydrate not to mention the mechanical de-risking of the plasma heating technology.

Another attractive and promising alternative is the partial or complete substitution of the combustion agent from natural gas or heavy fuel oil with Hydrogen. Hydrogen poses an attractive substitute as it has some similarities to natural gas

- State
- Adiabatic flame temperature in air
- Temperature of liquefaction

but also, quite a few differing properties

- Density
- Heating value (mass and volume based)
- Upper limit of flammability
- Minimum ignition energy ignition temperature
- Air requirements
- Combustion kinetics

These differing properties and their impact on calcination of hydrate need to be addressed, for example the impact on furnace design and subsequently flowsheet design or the effect on safety requirements, product quality of alumina, general combustion characteristics and emissions. Fuel substitution by hydrogen is a feasible way as there is no fundamental change required in the furnace design and existing plants can be retrofitted.

The use of hydrogen as combustion and reduction agent is not new in circulating fluid bed technology, Metso Outotec has applied it to the reduction of iron ore on an industrial scale, the plant produced more than 60 t/h of hot briquetted iron.

Figure 7. Aerial view of Metso Outotec's Hydrogen driven circulating fluid bed iron ore reduction plant built in Trinidad.

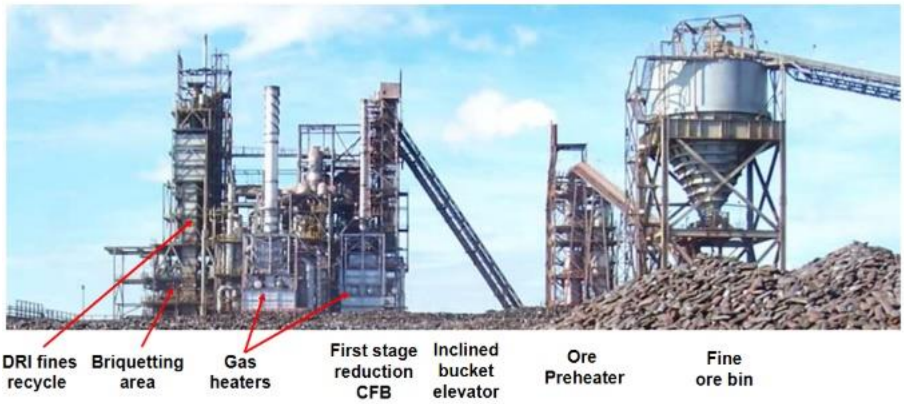

Figure 8. Ground level view of Metso Outotec's Hydrogen driven circulating fluid bed iron ore reduction plant built in Trinidad.

5. Conclusion

This manuscript introduces the highlights associate with decarbonizing the Bauxite to Alumina value chain as a contribution to overall Aluminium value chain decarbonization. The challenge associated in decarbonizing the alumina production process is highly orientated around key energy sinks and their interaction with energy "*conduits*" capable of relaying the renewable energy source to the intended destination. Each concept needs to be carefully considered based on the technology available, however the level of technical maturity based on capacity will ultimately determine the technology selected. This latter aspect is clear for the hydrometallurgical section of the Bayer process, as the technology selection would clearly depend on the size of individual technologies and the willingness of technology suppliers meeting a certain thermal demand.

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