Opportunities and Challenges of Bauxite Residue Valorisation from an Engineering Perspective – Revisit of Sintering Process

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Abstract

Bauxite residue is the key waste generated in the Bayer process for alumina production. The total global inventory of bauxite residue stored on land is currently estimated at over 6 billion tonnes and could reach beyond 10 billion tonnes by 2050, highlighting the significant environmental issues related to bauxite residue storage. Inaction or complacency with the current bauxite residue storage practices is not a responsible approach with regards to future generations. Process optimisation and valorisation of bauxite residue are desirable opportunities primarily to reduce the storage volume and extract other useful elements. However, due to its complexity and competition from other resources, the valorisation of bauxite residue is facing significant challenges, both commercially and regulation wise. This paper analyses these opportunities and challenges from an engineering perspective. A sintering flowsheet is presented for bauxite residue minimisation. Bauxite roasting is also discussed with the aim to address key questions: should thermal processing occur before Bayer digestion (bauxite) or afterwards (bauxite residue)? Will the traditional sintering process be re-born for valorisation of bauxite residue?

Keywords: Bayer process, Sintering, Alumina, Bauxite residue, Sustainability.

1. Introduction

Bauxite residue (BR), historically to be referred to as “Red Mud (RM)”, is the key waste material generated in the Bayer process for alumina production. Figure 1 shows the total global alumina production for the last 25 years [1], comparing with the estimated bauxite residue production. For every 1 tonne of alumina production, 1.5 tonnes of bauxite residue solids on average are assumed to be produced. Over the last 25 years the annual production of BR has increased by 180 %.

The total global inventory of BR stored on land was estimated to be around 2 billion tonnes in 2000 by Klauber et. al. from CSIRO [2]. Using this number as a basis in combination with Figure 1, the cumulative global BR storage is estimated and shown in Figure 2. About 6 billion tonnes of BR is stored worldwide nowadays, and this storage is expected to continuously increase dramatically in the future if no action is taken to recycle and re-use the residue.

The BR is commonly stored in various residue ponds (either dry or wet) close to individual alumina refineries. Often, the storage has occupied valuable agricultural land (Figure 3), has caused dusting and other environment issues, imposed a significant threat to local community, underground water, fauna and flora, and even wildlife if the storage is not managed strictly.

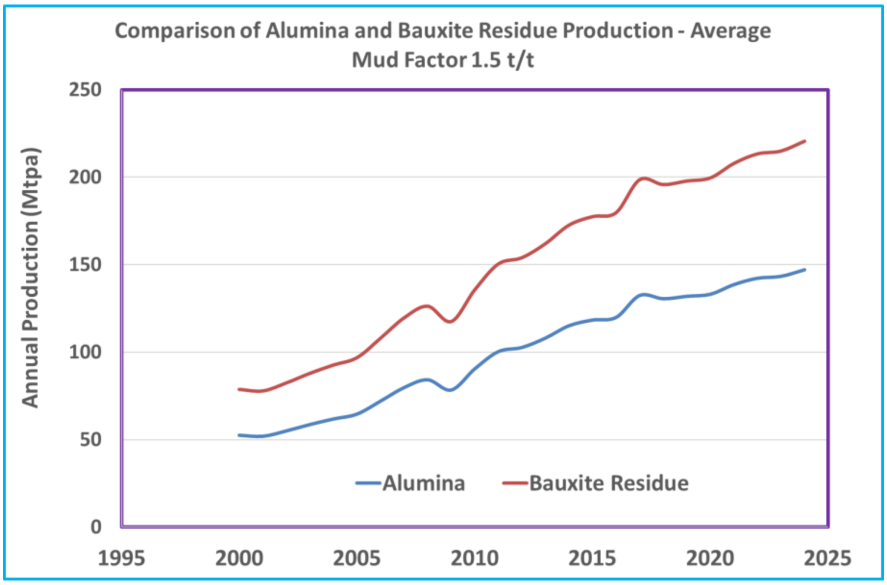

Figure 1. Comparison of alumina and bauxite residue production.

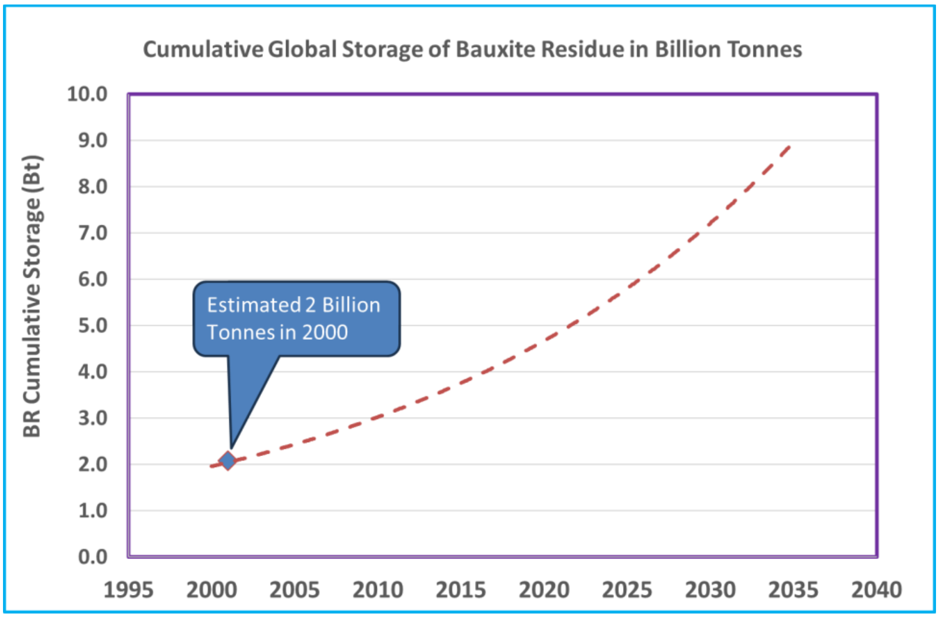

Figure 2. Cumulative global inventory of bauxite residue.

Figure 3. Bauxite residue pond near Stade (Germany) [3].

So, what do we do with the ever-increased amount of BR worldwide? Inaction or “complacency with the current bauxite residue storage practices” is not a responsible approach with regards to future generations. Looking for ways to minimise BR production and re-use BR then becomes a most desirable option to reduce the total storage volume.

Klauber et al. [2] have undertaken an extensive review on possible ways to re-use BR. These applications include wastewater treatment reagents, road construction materials, cement supplement and soil supplement. The purpose of this paper is to re-assess a way to reduce the volume of BR production and recover valuable materials. A case study is presented for a high-level discussion of cost and benefit considering the perspectives of engineering and sustainability.

2. Potential Values in Bauxite Residue

Bauxite residue generally contains the following key materials:

- Fe_2O_3 (hematite, magnetite, and goethite),
- Al_2O_3 (desilication product, gibbsite, boehmite, diaspore, tricalcium aluminate),
- TiO_2 (rutile and anatase),
- SiO_2 (desilication product and quartz),
- CaO (tricalcium aluminate and calcite etc.),
- Na_2O (desilication product and residue liquor phase caustic),
- Trace elements such as gallium, rare earth, scandium etc.

Based on Klauber et al. [2], the residue has on average 41 % Fe_2O_3, 16 % Al_2O_3, 9 % TiO_2, and 10 % SiO_2. Using this assumption, the inventory of these three major oxides is calculated and shown in Figure 4. Na_2O content in BR solids was estimated by assuming complete association with desilication product (DSP) in a Na_2O/SiO_2 molar ratio of 0.667.

These proportions cumulatively represent significant monetary values of metal oxides and others in the bauxite residue, indicatively over two trillion dollars. How to recover these values economically becomes a challenge that industries must overcome.

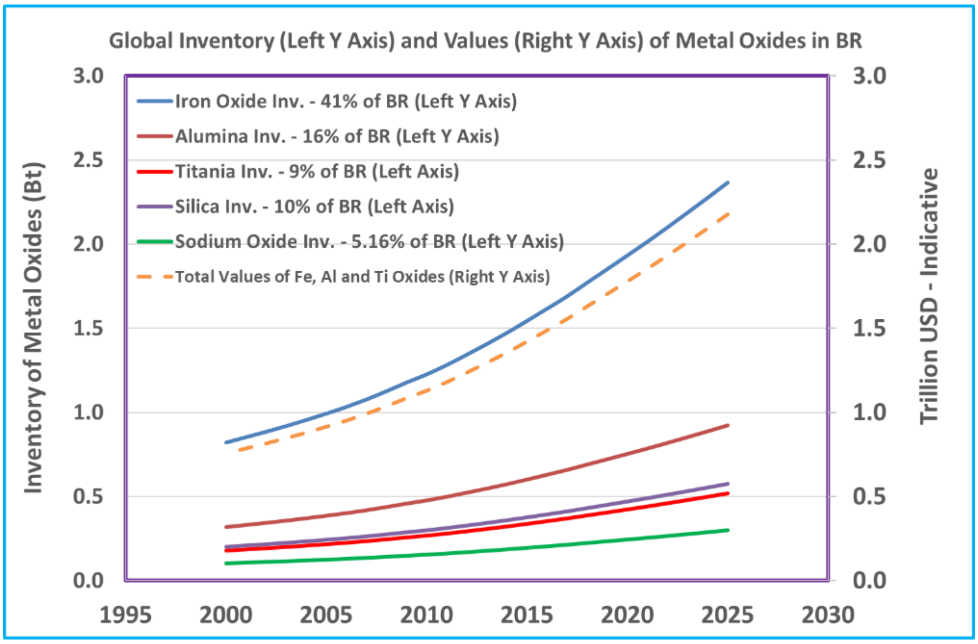

Figure 4. Cumulative inventory of metal oxides in BR and values of Fe, Al, Ti, and Na oxides (assuming: 80 USD/t Fe_2O_3, 350 USD/t Al_2O_3, 2 950 USD/t TiO_2, 452 USD/t Na_2O).

3. Outline of Potential Metallurgical Routes for Metal Recovery from BR

Metallurgical recovery of valuable metals from BR can in principle be done either via hydrometallurgy route (acid leaching) or pyrometallurgy route (smelting) process.

Hydrometallurgical recovery of values (Fe, Al, and Ti etc) from BR via acid leaching [4–6] requires significant consumptions of acids, in two aspects, caustic neutralisation and leaching of oxides. The flowsheet is expected to be complex related to impurities removal and likely takes up a large footprint with a potential requirement of solvent extraction and neutralisation processes. In addition, a hydrometallurgical process may potentially generate new waste products with new environmental risks or require significant extra cost for multi-stage treatment. That is besides the strong market competition from other better quality and lower cost raw materials than bauxite residue for extraction of these elements using acid leaching. For example, high quality hematite ore for iron making, and high-quality rutile or ilmenite for TiO_2 production are readily available from the market. Acid leaching of BR is therefore not considered economical and not further evaluated in this paper.

Among the various research works and patents [2], the pilot test work by the EU funded RemovAl collaborative research project [7] is perhaps the most progressed project in the field of pyrometallurgical recovery of Fe, Al from BR. Pilot plant tests involved the following steps:

- De-alkalise BR with the addition of lime (hydrothermal treatment of bauxite residue),
- Smelting the de-alkalised residue to produce pig-iron and an alumina containing slag (analogy to the Pedersen process for alumina production using bauxite [8]),
- The slag is alkaline leached to produce pregnant liquor for precipitation by carbonation,
- The alumina free residue slag is then processed for recovery of rare elements or other applications.

The present paper combines the de-alkalisation and smelting process into a sintering process to recover caustic and alumina in a rotary kiln. Iron oxide can be partially reduced to magnetite with addition of carbon, then separated with a high intensity magnetic process for sale to the market for iron making.

The advantages of this concept are:

- Well proven industrial experience and expertise, and can reduce residue volume significantly,
- More feasible to be integrated to an existing alumina refinery than a furnace smelter,
- Significant recovery of alumina and caustic from bauxite residue,
- Produce iron concentrate rather than pig-iron, resulting in less competition with steel industries,
- Produce grey mud for recovery of rare elements, or making cement or bricks, and other applications,
- Removal of organic carbon in sintering process and improvement of liquor productivity.

Figure 5 shows a high-level flowsheet which combines Bayer process with a sintering process in series. Bauxite residue produced in Bayer process is further treated in the subsequent sintering process for recovery of caustic and alumina. Carbon (coal) is added to reduce hematite to magnetite in the process. This sintering process is defined as “Reduction Sintering” like the process of “Reduction Roasting”.

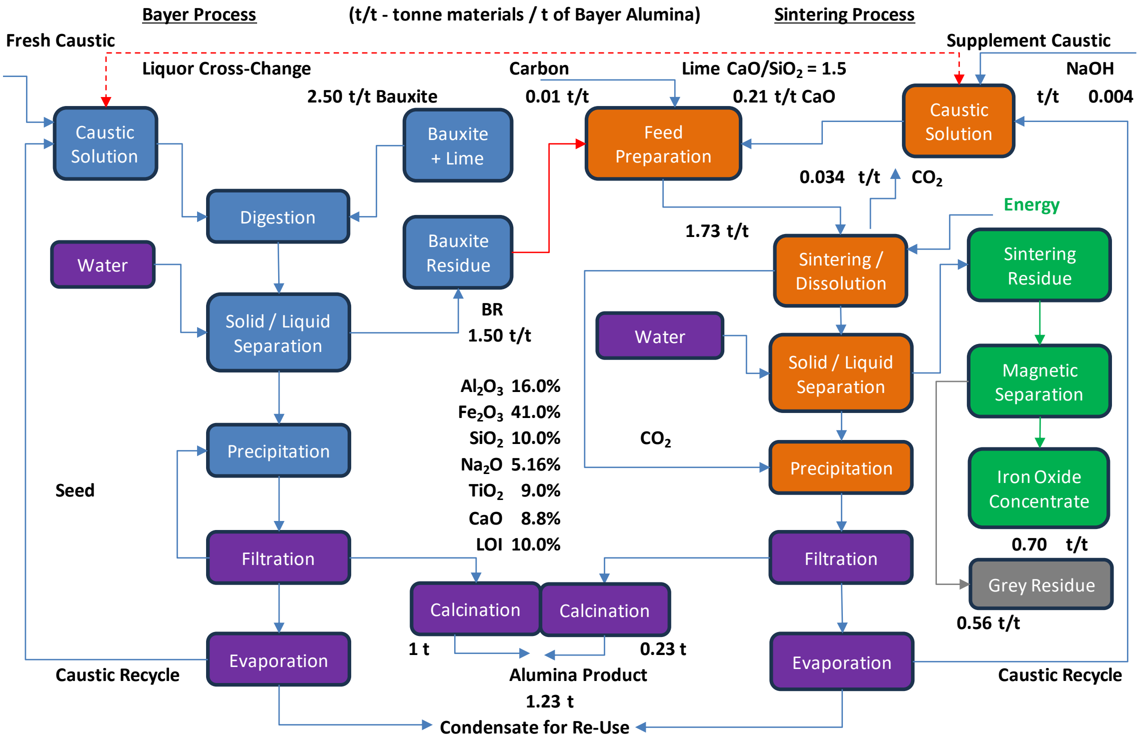

Figure 5. Flowsheet of reduction sintering + Bayer process.

A similar "Reduction Sintering" process is still practised in some of the alumina refineries, such as, in Kazakhstan and in China. Note, C as the reductant could potentially be replaced by biomass or by H_2 gas, but at a higher cost.

Capital investment related to Figure 5 is site specific and beyond the scope of this paper for evaluation. However, an analysis of Key Process Indicators (KPIs), costs, and benefits was done. with the results presented below.

4. Design Criteria and Key Process Indicators (KPIs)

To conduct a high-level mass balance calculation, key design criteria are presented in Table 1 for the flowsheet shown in Figure 5.

Table 1. Key process design criteria for the flowsheet of Bayer + sintering.

Key Parameters	Units	Values	Notes
Bauxite Factor	t/t Bayer Alumina	2.50	
Bauxite Residue Factor	t/t Bayer Alumina	1.50	
Fe_2O_3 in BR (Bayer)	wt % of BR Mass	41.0 %	As hematite
Al_2O_3 in BR (Bayer)	wt % of BR Mass	16.0 %	As DSP and alumina minerals
SiO_2 in BR (Bayer)	wt % of BR Mass	10.0 %	Completely as DSP
Na_2O in BR (Bayer)	wt % of BR Mass	5.16 %	Completely as DSP – simplifying assumption of full washed BR without consideration of associated caustic liquor
TiO_2 in BR (Bayer)	wt % of BR Mass	9.0 %	As rutile and anatase
CaO in BR (Bayer)	wt % of BR Mass	8.8 %	As CaO and Tricalcium Aluminate

Key Parameters	**Units**	**Values**	**Notes**
LOI in BR (Bayer)	wt % of BR Mass	10 %	Chemically bound water
CaO/SiO_2 in Sintering Feed	Mole Ratio	1.5	High-level assumption
$Na_2O/(Al_2O_3+Fe_2O_3)$ in Sintering Feed	Mole Ratio	1	High-level assumption
Carbon Charge to Sintering Feed	Mole Ratio of C/Fe	(1/12) × 1.2	1.2 times of stoichiometry: $C + 6 Fe_2O_3 = CO_2 + 4 Fe_3O_4$
Carbon Content in Bituminous Coal	wt %	60.0 %	Assuming resulting ash is 50 % Al_2O_3 and 50 % SiO_2
Sintering Energy Consumption	GJ/t Sintering Feed Solid	5.0	Equivalent to 37.8 GJ/t alumina
Al_2O_3 Recovery in Sintering	wt %	95.0 %	High-level assumption
Na_2O Recovery in Sintering	wt %	95.0 %	High-level assumption
Fe_2O_3 Recovery in Sintering	wt %	90.0 %	High-level assumption
Grade of Iron Concentrate	wt % Fe_2O_3	79.0 %	Derived from 55 wt% Fe concentrates (reported by Gu [9])
Soluble Soda Loss (Na_2CO_3)	t/t Bayer Alumina	0.020	Loss of soda in residue moisture

Based on the design criteria in Table 1, the key process indicators (KPIs) were calculated, and the results are presented in Table 2.

Table 2. KPIs of reduction sintering + Bayer process.

KPIs	**Units**	**Values**	**Notes**
Lime Addition in Sintering	t CaO/t Bayer Alumina	0.21	Cost of lime
Supplement Caustic in Sintering	t NaOH/t Bayer Alumina	0.004	Cost of 50 % NaOH
Bituminous Coal	t/t Bayer Alumina	0.015	60 % of carbon and 40 % ash (half to Al_2O_3 and half to SiO_2)
Sintering Alumina Production	t/t Bayer Alumina	0.23	Benefit
Fe_2O_3 Concentrate Production	t/t Bayer Alumina	0.70	Benefit
Na_2O Recovery	t/t Bayer Alumina	0.07	Benefit
Grey Mud Production in Sintering	t/t Bayer Alumina	0.56	37 % of the original 1.5 t/t. This is equivalent to 0.46 t/t total alumina production.

The chemical compositions of the grey mud generated are given in Table 3, showing significant reductions of Fe_2O_3, Al_2O_3 and Na_2O, more suitable for further processing as byproducts or disposal.

Table 3. Chemical compositions of grey mud (dry solid basis).

Components	**Units**	**Values**	**Notes**
Fe_2O_3	wt%	8.7 %	Major component
Al_2O_3	wt%	2.1 %	Insignificant amount
SiO_2	wt%	21.5 %	Major component
Na_2O	wt%	0.5 %	Much reduced caustic content
TiO_2	wt%	19.0 %	Major component
CaO	wt%	48.2 %	Major component
Trace Elements	Not accounted in this paper		

5. Analysis of Cost and Benefit

Base case cost of 1 t alumina refinery by a Bayer plant is shown in Table 4. The cost is broken down to the major items only with all minor items grouped as miscellaneous, taking up 5 % of the total cost. The costs of labor, maintenance and miscellaneous are high-level assumptions in percentages. The sale price of alumina is conservatively assumed as 350 USD/t, the gross margin is then 52 USD/t.

Table 4. Base case cost versus benefit – 1 t alumina by Bayer process.

Cost Items	**Consumptions, t/t or *GJ/t**	**Specific Costs, USD/ t or *USD/GJ**	**Total Cost, USD/t Al_2O_3**	**Percentages**
Bauxite	2.50	45	112.5	37.8 %
Lime	0.01	50	0.5	0.2 %
Caustic (100 % NaOH)	0.115	350	40.2	13.5 %
Total Energy*	10.0	7	70.0	23.5 %
Labor Cost			29.8	10.0 %
Maintenance			29.8	10.0 %
Miscellaneous			14.9	5.0 %
Total Cost			**298**	**100 %**
Gross Margin		**52**	**Assuming 350 USD/t sale price**	

Processing BR through sintering requires the addition of lime, caustic soda and carbon (e.g. coal), resulting in additional raw material costs. The total alumina production becomes 1.23 t as shown in Figure 5 and Table 2. The adjusted cost and benefit for the combined process (Figure 5) is presented in Table 5. The specific costs of labor, maintenance, and miscellaneous in sintering plant are arbitrarily increased to 1.2 times of the Bayer plant by considering the smaller production scale and some unique aspects in sintering.

Table 5. Adjusted cost versus benefit – 1 t of total alumina by Bayer and sintering.

Cost Items	**Consumptions, t/t or *GJ/t**	**Specific Costs, USD/ t or *USD/GJ**	**Total Cost, USD/t Al_2O_3**	**Percentages**
Bauxite	2.04	45	91.6	31.9 %
Lime in Bayer Process	0.008	50	0.4	0.1 %
Lime in Sintering	0.171	50	8.5	3.4 %
Caustic (100 % NaOH)	0.0072	350	2.3	0.8 %
Total Energy*	15.17	7	106	36.9 %

Cost Items	**Consumptions, t/t or *GJ/t**	**Specific Costs, USD/ t or *USD/GJ**	**Total Cost, USD/t Al_2O_3**	**Percentages**
Coal - Bituminous	0.013	100	1.3	0.5 %
Labor Cost			30.8	10.7 %
Maintenance			30.8	10.7 %
Miscellaneous			15.4	5.4 %
Total Cost	**(USD/t Alumina)**		**287.0**	**100 %**
Alumina Sale Price	(USD/t Alumina)		350	
Gross Margin from Alumina	**(USD/t Alumina)**		**63**	
Cost and Benefit of Iron Concentrate Recovery				
Cost of Magnetic Separation	USD/t Iron Concentrate		20	
Iron Concentrate Production	tonnes		0.70	
Iron Concentrate Sale Price	USD/t Concentrate		50	
Gross Margin from Iron Concentrate	**USD**		**21**	
Total Benefit	**USD**		**84**	

The analysis in Table 5 shows an increase of about 60 % in gross margin if a reduction sintering process is implemented to recover alumina, caustic soda, and iron concentrate as saleable product from the Bayer residue. The two third of this increase is due to iron concentrate sales. When iron recovery is disregarded, the increase in alumina profit margin is about 20 %. Also, it is worth noting a reduction of BR volume for future storage management will also result in a significant cost reduction, though it is not straight forward to evaluate as it is highly location related.

6. Opportunity for Reduction of Energy Consumption in Sintering

The most important cost in sintering process is the energy cost. Figure 6 shows the gross margin and specific energy consumption per tonne of alumina produced by sintering as a function of specific energy per tonne of sintering feed solids. The current assumption of 5 GJ/t sintering feed solid, equivalent to ~38 GJ/t Al_2O_3 by sintering, seems have sufficient buffer zone for a safe investment. It seems 8 GJ/sintering feed solid (closely equivalent to 60 GJ/ t Al_2O_3 by sintering) is the maximum tolerable energy consumptions in sintering for a cash positive investment (not considering payback required on the capital expenditure).

For reference, an average energy consumption with mixed flowsheets (2 % sintering, 4 % combined and 94 % Bayer) in China was about 12.5 GJ/ t Al_2O_3 as reported in 2015 [9]. For a pure sintering plant, 40.19 GJ/ t Al_2O_3 has been reported in the literature [10].

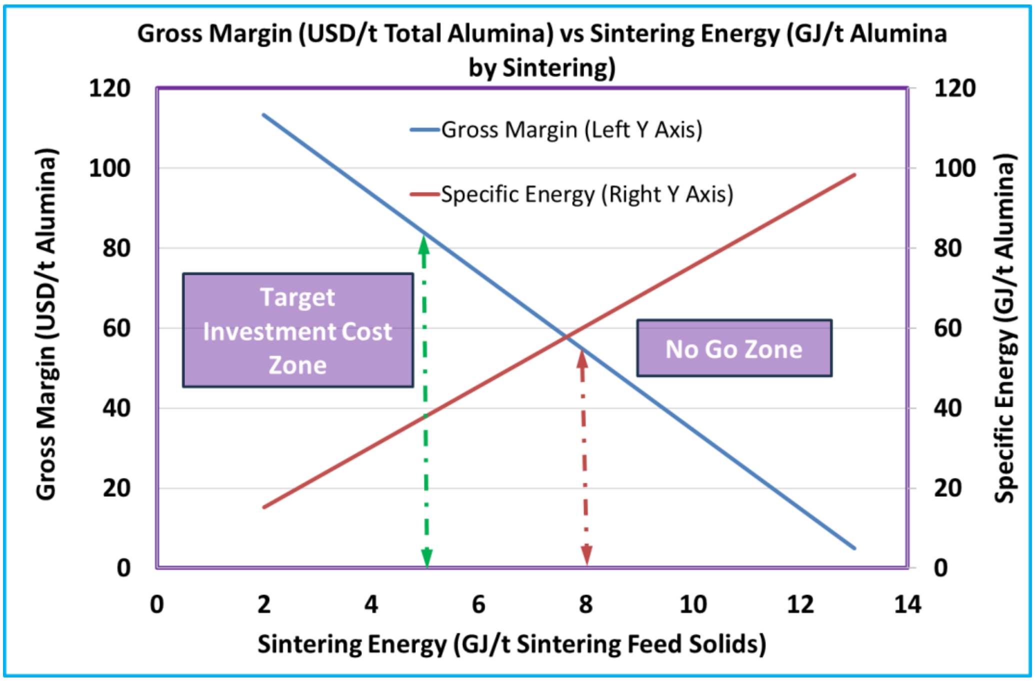

Figure 6. Variation of gross margin with sintering energy consumption.

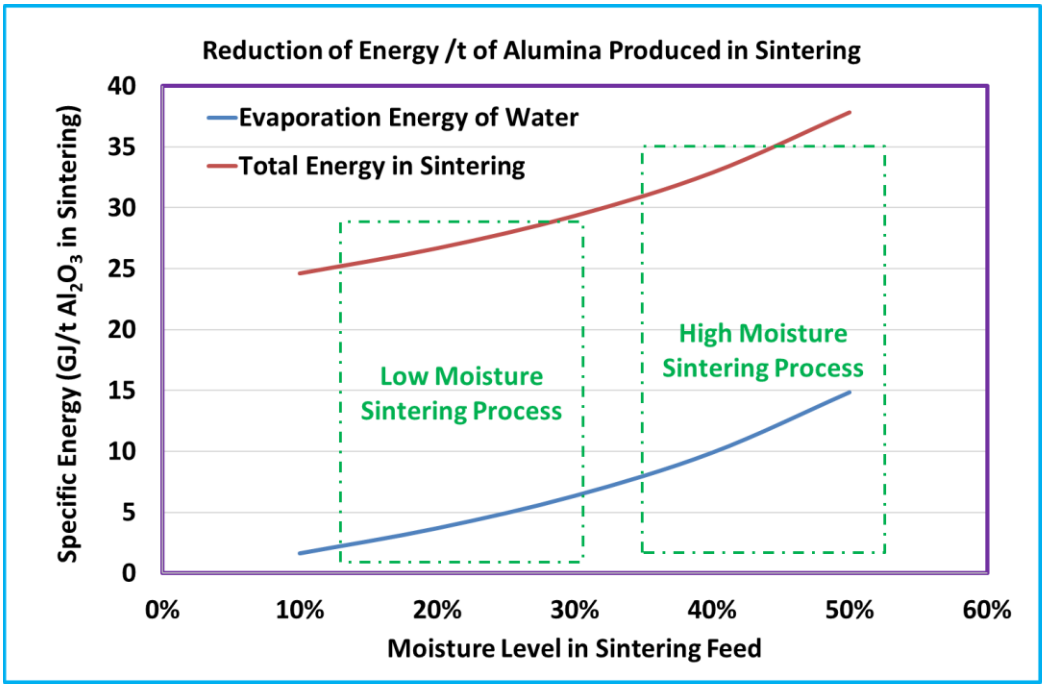

Figure 7. Variation of specific energy in sintering with moisture level.

In the conventional sintering process, feed is in slurry form with 40 to 50 % water content by mass. A significant amount of energy is therefore required for evaporation of this water. Moving away from the High Moisture Sintering Process (40 to 50 % water in slurry feed) to Low Moisture Sintering Process (20 to 30 % water in slurry feed) would reduce the sintering energy consumption to a certain extent. Figure 7 shows the variation of specific energy use per tonne of alumina in the sintering process, with a potential reduction from 38 to less than 30 GJ/t Al_2O_3. An additional benefit with Low Moisture Sintering could be to use a higher efficiency reactor such as fluidised bed. However, more engineering investigation is required for this Low Moisture Sintering Process.

7. Sintering versus Bauxite Roasting

In contrast to BR sintering in the back end of Bayer plant, there is potentially a competitive opportunity of bauxite reduction roasting in the front end of Bayer plant. Iron concentrate could also be produced after the roasting by using similar high intensity magnetic separation. This paper provides a high-level comparison of the two processes in Table 6, without undertaking an in-depth analysis.

In author's opinion, sintering is likely more feasible than bauxite roasting in terms of integration into the existing Bayer alumina plant if the required footprint is available. However, it is open to the readers and the industry for constructive technical debate and competitive development in the future.

Table 6. High level comparison of bauxite roasting and BR sintering.

Process	Pros	Cons
Bayer => Reduction Sintering => BR	Recovery of alumina, caustic soda, iron concentrate, reduced volume of materials to be sintered after Bayer alumina extraction, more compatible for integration with the existing Bayer process.	Scaling issue, carbonation precipitation is normally required, potentially fine size alumina product, carbonate input and output balance in the circuit, use of carbon as reductant (though could potentially be replaced by H_2), energy cost.
Reduction Bauxite Roasting => Bayer => BR	Removal of organic carbon, potential change of bauxite mineralogy to improve the desilication process, low water input due to removal of chemical water with bauxite, lower bauxite residue mud washing load.	Higher volume of materials to be roasted with associated energy cost, potential impact on alumina extraction due to dehydration of gibbsite or requiring higher digestion temperature for an equivalent extraction, need for surge capacity of roasted bauxite ahead of Bayer process, less compatible for integration with the existing Bayer process.

8. Conclusions and Recommendations

This paper demonstrates that reduction sintering process is a viable process for valorisation of BR with the potential for reduction of its mass by 63 %. The process economy in terms of gross margin could potentially be increased by 60 %.

Potential reduction of energy cost in sintering could also be possible if the concept of Low Moisture Sintering Process is feasibly implemented. However, this needs further engineering evaluation. Using such process, a more energy efficient reactor such as fluidised bed may potentially be used.

As correctly pointed out by Klauber et al. [2], the challenge for the industry, governments, and other stakeholders is to work together to identify specific projects within key priority areas for further development. This paper agrees this would likely be a site by site or regional basis rather than a unique solution for all projects globally. The benefit which can realistically be achieved depends on several factors: bauxite / residue compositions, energy price, decarbonisation strategy and status, potential market for use of new products generated from bauxite residue such as, iron concentrate and grey mud (or further processed products). Impurities balance is another critical issue which requires to be evaluated.

As one of the key industrial stakeholders, engineering consulting firms bear responsibilities for continuous improvement of techno-economic solutions for alumina refining and bauxite residue management. Worley is dedicated to a proactive role in delivering a more sustainable world!

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