Decarbonisation of the Bayer Process – A Technical Assessment of Enabling Technologies and Process Economics

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Abstract

This paper reviews the scale and nature of the decarbonisation challenge faced by the alumina refining industry globally and provides a technical assessment of potential retrofit pathways to reduce carbon emissions associated with the Bayer process. Three aspects of this challenge are considered. Firstly, the energy footprint of the industry is considered both from a global perspective, as well as detailed mapping of the energy flow through the Bayer process to highlight key areas of energy consumption and waste. Secondly, emerging and established technologies are investigated that have the potential to support decarbonisation through process electrification, low-grade energy recovery, and the reduction/elimination of cooling water requirements. Methods are proposed for the recovery and reuse of each low-grade energy loss from the process. A refinery-wide retrofit case study is then detailed, which applies a selection of these methods to eliminate the requirement for boiler generated steam during normal operation. The resulting Bayer energy footprint, CO_2 abatement achieved, economics, practical considerations, and challenges are discussed. Lastly, technologies are reviewed that have the potential to eliminate the residual fossil fuel requirement including green calcination, electrified steam generation, and on-site thermal energy storage.

Keywords: Decarbonisation, Electrification, Thermal energy storage, MVR, Heat pumps.

1. Introduction

Since the Paris Agreement on climate change came into effect on November 4, 2016, governments and industries around the world are committing to reducing their emissions and setting net zero targets. While these targets demonstrate commitment towards decarbonisation, the required engineering and technological solutions necessary to achieve these targets represent an immense challenge for the entire alumina industry. Further, there is a general lack of technically mature or commercially viable solutions and, as such, alumina refining is designated as a 'hard-to-abate' industry.

This paper aims to provide a comprehensive technical overview of the scale and nature of the challenge, the various approaches that show promise in enabling step reductions in Bayer energy consumption, and the technologies that may enable full transition to renewable energy sources.

With an initial objective to reduce net energy input into the process, a detailed mapping of energy flow through the Bayer flowsheet is presented, and the sources of significant energy losses are identified. Technology configurations are then proposed for the recovery of each of these low-grade energy sources into usable steam for process heating. For each technology configuration, a conceptual flowsheet is presented and major design constraints, engineering challenges, and practical considerations are discussed. Indicative capital costs are presented per application, and a refinery-wide retrofit approach is then proposed such that the need for continual boiler generated steam is eliminated. Methods for non-fossil fuelled steam generation are considered, along with potential alternatives. Finally, initiatives focused on the development of green calcination technologies are discussed.

2. Industry Overview

In 2021 the global alumina refining industry produced 130 million tonnes of metallurgical (smelter) grade alumina, consuming approximately 1 300 petajoules (1 PJ = 10^{15} J) as direct process energy input (Figure 1) at an average specific energy of ~10 gigajoules per tonne alumina produced [8, 10].

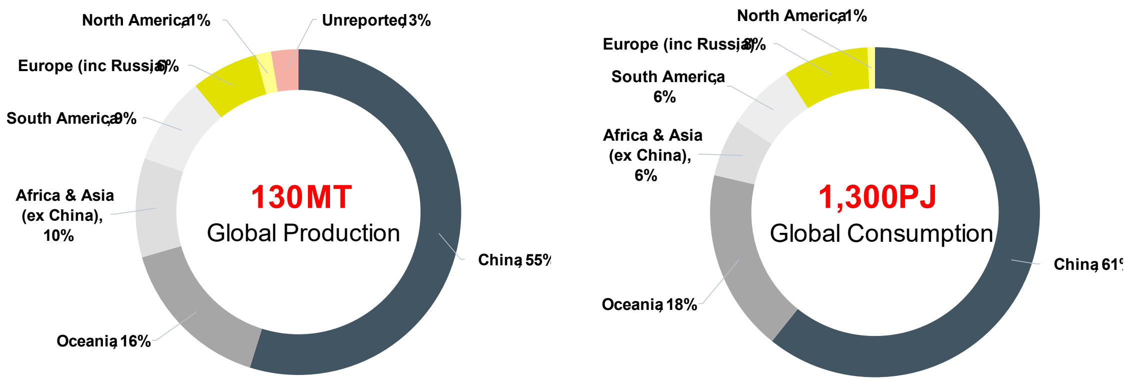

Figure 1. Global alumina production and energy consumption [8, 10].

To put the alumina industry's global energy requirement into context, if supplied as 100 % electrical energy it would exceed the total electrical generation capacity of most developed countries, placing it between Iran (11th largest at 1 288 PJ) and France (10th largest at 1 970 PJ) [5]. Hence, as illustrated in Figure 2, the energy footprint of the alumina refining industry is comparable to that of the total electrical generation capacity of a large country, albeit distributed globally.

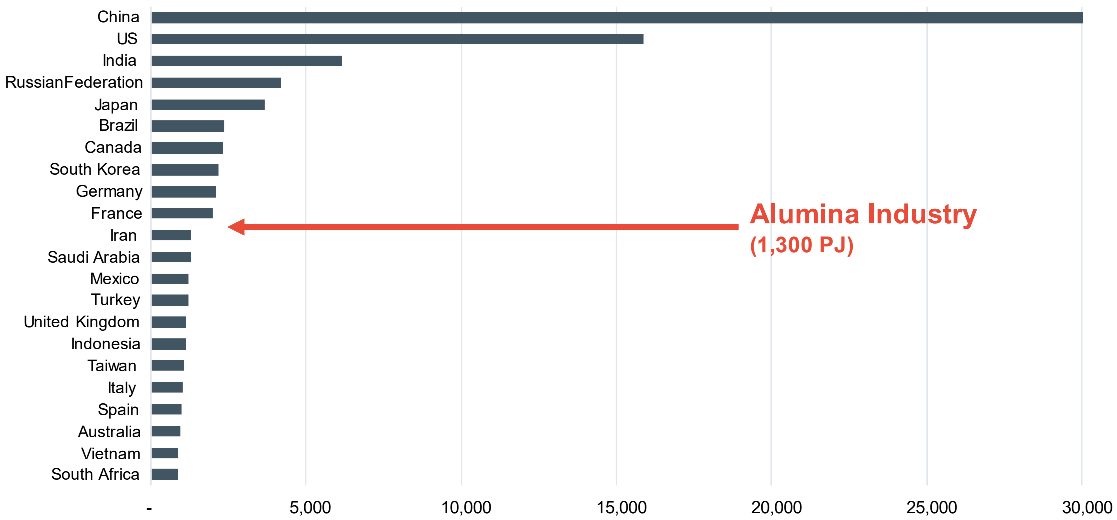

Figure 2. Electricity generation by country [5].

Over the past two decades global metallurgical alumina production has increased nearly 250 %, increasing the global energy footprint significantly. However, within this timeframe the average specific refining energy, and hence specific carbon emission, has reduced by approximately 30 % [1]. This has been achieved, in part, through efficiency improvements resulting in highly optimised core flowsheets. While further step-reductions in specific energy consumption are thus package 2 is completed, it is anticipated the calciner can be operated for 2 hours using 100 % hydrogen fuel [3].

5.3.2 Electric Calcination

Electric calcination involves substituting natural gas with electric heating that is renewably sourced. Like hydrogen calcination, electric calcination also promises to produce near-pure steam [2] that can be recovered and reused in the Bayer process via simplified variants of the configurations discussed in Section 4.2.5. However, less steam is comparatively produced as there is no combustion of hydrogen to produce additional water vapor.

Moreover, as electric calcination relies directly on intermittently available renewable electricity and is vulnerable to any upsets in the grid, energy storage is required for firming and ensuring continuous power supply [1]. This contrasts with hydrogen calcination where excess hydrogen may be produced and stored when excess renewable power is available.

6. Conclusion

The alumina industry is faced with the significant challenge of finding economical ways to decarbonise the ‘hard-to-abate’ Bayer process. There is a general lack of technically mature or commercially viable technologies that may enable such step reductions in carbon emissions through transition to renewable energy sources. Rather, the industry must look sideways to adopt low-grade energy recovery and electrification technologies from other industries, as well as pioneer the development of new technologies that enable electrification of fossil fuel driven unit operations such as electric or hydrogen fuelled calcination.

This paper presents a case study for a typical modern Gibbsitic low temperature flowsheet that has been fully retrofitted with low-grade energy recovery systems to eliminate the need for continual fossil fuel fired steam generation. At a capital cost ranging from 130 to 180 USD per tonne/annum refinery capacity for a brownfield retrofit, this represents a significant investment. However, such retrofits reduce electrical supply requirement for site steam generation by a factor of 3 compared to steam generation via conventional alternatives, such as electric boilers.

Significant modifications are required to the Bayer process to retrofit the proposed low-grade energy recovery systems. This introduces numerous technical challenges and practical considerations that must be overcome. However, through careful engineering, these challenges are surmountable. Ultimately, the pathway for decarbonising the alumina industry will only be resolved through the incremental adoption of low-grade energy recovery and electrification technologies, followed by the transition to fully electrified process heating.

7. Acknowledgement

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