Towards Greener Aluminium Production - A Carbon Footprint Assessment of Graphitized Cathodes for Electrolysis Pots

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Abstract

Aluminium (Al) production generates approximately 1 % of worldwide greenhouse gas emissions (270 Mt CO_2eq. in 2022). Even though the demand for cathode blocks for aluminium electrolysis pots is only around 5 kg/t Al produced, the production of carbon and especially graphite cathodes is energy intensive. Therefore, it is essential to evaluate the carbon footprint of such products.

In this paper, a cradle-to-gate assessment of graphitized cathode blocks based on our Polish operation in Nowy-Sącz is conducted, building upon previous work done on our French product. The life cycle assessment (LCA) methodology is utilized with a specific focus on the carbon footprint.

The production steps that contribute the most to greenhouse gas emissions include coke calcination, block baking and the graphitization treatment that follows. Hot spots in term of carbon footprint include raw material production, energy consumptions and process emissions resulting from volatiles combustion during heat treatment. For both our Nowy-Sącz and French products, actual emission values as well as process optimizations and the influence of electricity grid mix will be discussed to work towards a more environmentally friendly aluminium production.

Keywords: Life cycle assessment, Carbon product footprint, Graphite cathode block, Aluminium reduction technologies, Low carbon aluminium.

1. Introduction

Even though secondary aluminium production emits fewer greenhouse gas (GHG) than primary aluminium production, the latter represents today more than 60% share of global aluminium production volumes and will significantly increase its production capacity over the next decades [1]. In 2022, primary aluminium production was responsible for approximately 1 % of global GHG emissions [2].

As the aluminium (Al) industry strives to reduce its GHG emissions, the aluminium carbon footprint has already been studied and improved over the past 25 years. In 2012, a review inventoried 24 assessments of aluminium carbon footprints (CF) with a typical range of 9.7–8.3 t CO_2eq./t Al [3]. Current global industry average is 12.7 t CO_2eq./t Al [4]. The main GHG emissions originate from the alumina refining process, the anode consumption with approximately 0.4 tC/t Al released in the atmosphere, equivalent to 1.5 t CO_2eq./t Al and the electricity consumption (if not from low-carbon source) with approximately 13 kWh electricity/kg Al [5]. Until 2024, there had been no assessment dedicated to evaluating the cathode carbon footprint. Consequently, most of recent assessments of aluminium carbon footprints did not consider the contribution of cathode production to the aluminium carbon footprint [1].

In 2024, the first study dedicated to assessing Tokai COBEX's French (TCX-FR) graphitized cathode (best-in-class material) using a life cycle assessment (LCA, also called life cycle analysis) methodology was conducted. This assessment is based on a lengthwise graphitization (LWG) process route [1]. This paper presents a new CF assessment investigating the Tokai COBEX's Nowy-Sącz (TCX-NSZ) graphitized cathode production process. Although also based on a LWG process route, there are differences in the processes of both countries. Therefore, this assessment will simultaneously continue to build knowledge of GHG emissions along the graphitized cathode processes while providing a better understanding of the process influence on these emissions.

2. Material and Methods

This section introduces the global scope of the assessment and details the data collection and treatment required to obtain a complete life cycle inventory of the TCX-NSZ graphitized cathode. The scope and hypothesis have been determined based on the previous study of TCX-FR production [1] to allow for a fair comparison with the TCX-FR graphitized cathode.

2.1 Goal and Scope

Like the previously published assessment, this CF assessment also follows the *Life Cycle Assessment* methodology standardized in ISO 14 067. This method is considered the most robust and renowned for quantitatively evaluating the potential environmental impacts associated with a product, process, or service throughout its life cycle stages. The goal and scope of this assessment are similar to those of the previous study, allowing for comparability. The *goal of the study* is to conduct an attributional CF assessment of the production of graphitized cathodes for aluminium smelter (primary aluminium production) to identify its main contributors and potential process improvements. This objective is also achieved through the process influence comparison with the TCX-FR graphitized cathode [1]. A cradle-to-gate *system boundary* is considered to account for all emissions associated with cathode production. Details about the flows included in the system are provided in section 2.2. The *functional unit* is one tonne of graphitized cathode, as typically produced in the cathode production plant, with slots for collector bars but excluding metal collector bars (usually added at the aluminium smelter facility as part of the lining operation). The *foreground system* includes the factory of Tokai COBEX, located in Nowy Sącz, a European graphite and carbon products manufacturer with plants involved in cathode production for aluminium smelting for more than a century. The foreground system is based on primary data collected in the plant over 2022. The *background system* is modelled using the *Sphera® MLC* 2023.1 database (*Managed LCA Content®*, former *GaBi DB®*). The system modelling and calculation are done using the *Sphera® LCA for expert* software (Previously *GaBi®*) [6]. The selected impact assessment method is the *Climate Change total* impact category of the European *Environmental Footprint (E.F.) 3.1* [7].

2.2 System Boundary and Process Description

Figure 1 introduces an overview of the system boundary for the production of graphitized cathode at TCX-PL.

The study considers a cradle-to-gate system boundary to account for all impacts (including upstream) associated with the production of one ton of graphitized cathode. A mass allocation strategy is implemented to consider valuable material losses that are internally re-used in the plants or sold externally. The foreground system consists of primary data from plant operation in 2022, some of which requiring simplification treatment (as subdividing of all flows is not possible to specifically consider the cathode production). The modelling and background data rely on the *Sphera*®'s international Life Cycle Assessment software and database, respectively. Both the data collection and the modelling choices have been made in accordance with the previous TCX-FR cathode production study. The few remaining differences have been detailed and are expected to have a limited impact on the result.

A CF of 5.5 t CO_2eq./t graphitized cathode is calculated based on the national average electricity mix in Poland, which is then reduced to 3.3 t CO_2eq./t when accounting for guarantees of origin purchased by Tokai COBEX in Poland. This value is primarily influenced by energy consumptions (58 % overall, in the case of an average polish electricity mix), material production (32 %) and process emissions (9 %).

The manufacturing process of TCX-NSZ graphitized cathode is more efficient in terms of materials and energies compared to the TCX-FR production process, also resulting in lower process emissions. Additionally, the delivery of raw materials to the plant by train contributes to a decrease in CF. However, without considering guarantees of origin, the higher polish average electricity mix offsets the CF gains of the efficient TCX-NSZ process. This comparison is based on the previous study of the TCX-FR process which determined a CF of 4.1 t CO_2eq./t cathode.

Finally, a sensitivity analysis enables the emphasis on the role of the electricity CF contribution which leads to a graphitized cathode CF ranging from 2.8 to 6.4 t CO_2eq./t for the best-case scenario of French-average electricity mix and the worst-case scenario of coal-fired electricity, respectively.

The study highlights the major contributors to the cathode production CF that should be carefully considered in the future to promote lower GHG emissions. Specifically, the electricity mix and the raw materials carbon footprint are identified as the main drivers of the product CF. In the TCX-NSZ plant, the electricity contribution could be decreased by using a higher share of guarantees of origin. In the TCX-FR plants, there is likely room for process operation improvement as both TCX-NSZ and TCX-FR plants use similar processes but show significant differences in energy and auxiliary material consumptions.

Within the range of 3–6 t CO_2eq./t cathode, this study confirms the significant GHG emissions associated with the production of cathodes for aluminium smelters. Regardless of the CF methodology chosen and the hypothesis, the use of fossil auxiliary materials and raw materials is linked to a substantial portion of the impact (about 2.3 t CO_2eq./t cathode). These emissions come from both the production of these materials and the process emissions they generate and are common across all production plants. Therefore, achieving net carbon neutrality by 2050 [14] will likely require addressing the sourcing of these carbon-rich materials as of the biggest challenges.

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