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Techno-economic study of CO_2 capture for aluminum primary production for different electrolytic cell ventilation rates

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HIGHLIGHTS

- 4% CO_2 concentration in the flue gas is the most economical and technical configuration for CO_2 capture.
- The waste heat recovery allows to reduce by 58% the cost of capture.
- In the most favorable case, the capture cost is 100.15 $/ton Al (4.86% increase on the aluminum price).
- With thermal integration and incomes from tax, the capture represents 2.06% increase on its actual production cost.

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ABSTRACT

As several other industries, primary aluminum production faces the challenge to reduce its greenhouse gas emissions, mainly composed of carbon dioxide (CO_2). This work presents a techno-economic analysis of the implementation of a carbon capture plant specifically designed for a primary aluminum smelter, in order to investigate the feasibility to reduce CO_2 emitted by electrolytic cells. It allows to verify if the capture using the traditional monoethanolamine (MEA) aqueous solutions can be economically attractive for the aluminum industry. The CO_2 capture plant was sized and optimized taking into account typical aluminum production characteristics and several possible ways to capture CO_2 were investigated. The effect of the increase of CO_2 concentration in the flue gas (that could be achieved by reducing cell ventilation) and of plant thermal integration were taken into account in order to reduce the capture costs. It appears that 4 vol% CO_2 concentration in the flue gas is the most economically and technically sound configuration. In addition, waste heat recovery allows to reduce by 58% the cost of capture if waste heat recovery is available in the primary aluminium smelter. Overall, the cost of capture could only represent 2.06% increase on its actual production cost (with carbon tax).

1. Introduction

Global warming has become a critical issue during the last decades. The raise of temperature at the surface of the globe is attributed to the increased levels of greenhouse gases (GHG) in the atmosphere, mainly resulting from human activities. Carbon dioxide (CO_2) is the principal greenhouse gas. Its atmospheric concentration is increasing at an accelerating rate (from 280 ppm in 1750 to 394 ppm in 2012) [1]. In this context, various governments around the world have established ambitious GHG emissions reduction targets. For example, European countries instituted in 2005 the first carbon trading market in the world (European Union Emissions Trading Scheme, EU ETS). The province of Quebec has joined three other Canadian provinces and seven US states to create the second largest carbon exchange market. The government of the province of Quebec has committed to reduce the overall GHG emissions of the province by 20% (compared to the level of 1990) by 2020 [2] and as mentioned above, is about to launch a carbon market. Starting from January 2013, all industries of the province that produce more than 25,000 tons of CO_2 per year will have to comply with emission allowances. If an industry exceeds its quota, the bottom price is set at 10 $ per ton of CO_2 released. This price may also evolve. This is the case in Europe, where it is considered to raise the price of the ton CO_2 by reducing emission allowances. Such regulation represents an additional incentive for reducing industrial GHG emissions.

Primary aluminum production is an important industrial sector in the Province of Quebec. In 2010, Quebec's aluminum production accounted for 3.1 million tons of aluminum per year or approximately 7% of the world production [3]. The CO_2 emissions of the aluminum industry come from two main sources: indirectly, from

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the energy required in the processes (Table 1) and directly, from the consumption of carbon anodes in the Hall-Héroult process. The amount of CO_2 emissions related to electricity depends on the electricity source (e.g., nuclear, hydro, coal). In Quebec, since electricity is mainly from hydroelectric source, the main CO_2 source of the aluminum sector is the anode consumption. The annual CO_2 emissions of Quebec's aluminum industry represent approximately 9 million tons of CO_2 [4]. Like many other industries, the primary aluminum sector faces the challenge to reduce its GHG emissions.

One of the most practical approaches to meet this challenge in the short term, without affecting significantly the current processes and equipment, is the carbon capture and storage (CCS) from exhaust gases from electrolytic cells [5]. Carbon capture technologies have already been widely studied for applications such as coal fired power plants, but very few efforts have been devoted specifically to aluminum industry [6]. However, because of the inherent features of the effluents produced by primary aluminum smelters, current carbon capture technologies approaches cannot be applied straightforwardly. Therefore, the present paper focuses on the capture of CO_2 emitted directly by the electrolytic cells, i.e. from the CO_2 released by the consumption of the anodes in the Hall-Héroult process.

So far, this topic has been widely ignored; only two publications in conference proceedings on CO_2 capture from aluminum electrolytic cells have been found in the open literature. Lorentsen et al. [7] cited the CO_2 emitting sources in the aluminum industry and proposed a new design of the flue gas collecting unit which would be located closer to the holes in the crust of the electrolytic cell. According to their measurements, this design can lead to a reduction of the net gas suction volume, corresponding to 4 vol% CO_2 concentration (compared to ~1–1.5 vol% CO_2 concentration in the current operation conditions). Broek and Save [6] discussed the possibility of carbon capture using amine solution or chilled ammonia, in the absence and the presence of sulfur dioxide in the flue gas. However, the design of the CO_2 capture plant for integration in the primary aluminum smelter and the technical and economic feasibilities have not yet been addressed. So far, published techno-economic analyses have mostly covered CO_2 capture process using aqueous MEA and have principally considered the removal of CO_2 from power plant [8–12] and cement plants [13].

Considering the nature of the gaseous effluents from primary aluminum smelters (i.e., low pressure ($\sim P_{atm}$), low concentration (vol% < 4)) and the fact that the capture technology has to be easily adapted to an existing plant, the most appropriate capture technologies for this application are based on chemical absorption of CO_2 [14]. Since amine-based system capture is a mature technology applicable to retrofit configurations, contrarily to the chilled ammonia system [15], the present work focuses on the CO_2 capture using aqueous monoethanolamine (MEA) solutions as absorbent.

In this work, we present a techno-economic analysis of the implementation of a carbon capture plant specifically designed for a primary aluminum smelter. The novelty of this work lies in the fact that the CO_2 capture plant was sized and optimized taking into account typical aluminum production characteristics. Along with aluminum, a huge and almost pure CO_2 flow (traces of impurities) is produced in the chemical process; however, surprisingly, the CO_2 is very hard to recover because the gaseous flow becomes extremely dilute due to the ventilation system. In this study, we therefore investigated from a techno-economic point of view several possible ways to capture CO_2.

Table 1
Life-cycle GHG emissions from a modern primary aluminum smelter, from [7].

Source of electricity	Hydro kg CO_2 eq/kg Al	Gas-fired power kg CO_2 eq/kg Al	Coal-fired power kg CO_2 eq/kg Al
Alumina production	1.80	1.80	1.80
Anode production	0.30	0.30	0.30
Electrolysis – carbon	1.50	1.50	1.50
Electrolysis – AE	0.30	0.30	0.30
Casthouse	0.06	0.06	0.06
Electric power	0.14[a]	5.80	13.60
Total	3.96	8.76	17.56

[a] [49,50].

First, the capture designed for the main CO_2 emission source, the electrolytic cells, was not only based on the current operation conditions (CO_2 concentration and temperature), but the system was also designed considered two other possible scenarios for CO_2 capture (increase of CO_2 concentration corresponding to different ventilation rate of electrolytic cells), in order to evaluate possible benefits that might justify a redesign of the electrolytic cells, a study which is presently in progress in our research group. The modifications in temperature related to the increase in CO_2 concentration were taken into account in the design of the installation. Second, in order to take into account the important amount of thermal energy which is lost in several sectors of a primary aluminum production facility, the potential of coupling the CO_2 capture plant with a waste heat recovery strategy was also investigated for each of the CO_2 concentration scenario mentioned above. Taking into account that a large amount of heat is required in the capture process, the heat recovery is expected to contribute to the reduction of the impact of CO_2 capture (energy input required and supplementary CO_2 emissions). The most interesting waste heat sources in a typical plant were therefore identified considering the capture plant features. To the best of our knowledge, no similar work is available in the open literature.

In order to evaluate the costs and benefits of the capture facility with the technology available on the market, a comprehensive flowsheet model was built using Aspen Plus® and the costs were estimated with APEA®. For each case mentioned above, the influence of the key design parameters (packing height of the absorber, packing height of the stripper, and absorbent composition) were analysed and the main installation components (absorption and stripper columns) were designed and optimized in order to find the best performing and cheapest configurations. The analysis was performed on the basis of typical data of Alcoa primary aluminum smelter which were provided by Alcoa Deschambault Québec (ADQ).

2. Description of primary aluminum smelters and effluent particularities

Aluminum production technology ultimately affects the flow rate, temperature and composition of the gases to be treated. A process description is therefore required in order to understand the different scenarios considered in this work.

The Hall-Héroult process is the most widely used for the production of primary aluminum. Alumina (Al_2O_3) is dissolved in a cryolitic bath and an electric current passes through the bath between a carbon anode and a cathode. The overall reaction can be expressed as:

$$2Al_2O_3 + 3C \xrightarrow{\text{electricity}} 4Al + 3CO_2 \quad \Delta H^{\circ}_{298} = 478\ \text{kcal/mol} \tag{1}$$

As aluminum is produced, it accumulates at the bottom of the electrolytic cell due to its higher density in respect to the cryolitic liquid. A typical cell is shown in Fig. 1. To produce one ton of Al with the current technology, between 12 and 15 MWh of electricity is required. In itself, this large energy consumption can contribute significantly to GHG emissions depending on how electricity is produced (Table 1). In the process, the carbon electrodes (anodes)