CO2 Capture and Management Strategies for Decarbonizing Secondary Aluminium Production

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Abstract

The production of aluminium largely depends on the use of fossil fuels, resulting in the emission of significant amounts of greenhouse gases. As the aluminium industry is working towards decreasing its environmental burdens, the elimination of direct emissions from the remelting step becomes increasingly important. This research presents opportunities for decarbonizing secondary aluminium remelting and rolling via optimized carbon capture and abatement routes. Various carbon capture and management strategies for secondary aluminium production sites are developed and evaluated. To this end, process integration and optimization techniques following a mixed integer linear programming (MILP) approach are applied. A blueprint of an aluminium plant is developed, and the integration of several carbon capture and management technologies is modelled. The studied capture options include oxy-combustion, amine-based absorption, membranes, structured solid sorbents, and cryogenic beds. Once captured, the concentrated CO2 gas stream can be pressurized for pipeline transport or injection, transformed into synthetic natural gas, mineralized into cement additives, or used to produce plastic monomers. A systemic approach was adopted to compare these options in terms of multiple performance indicators. It was found that, up to 80% of the emitted CO2 can be efficiently captured and utilized. Moreover, additional revenue from mineralized CO2, olefins, or synthetic natural gas results in a net negative change in operating expenditures of the plant with comparison to continuously emitting the base flows of fossil CO2. Methanation provides a potential defossilization route when coupled with the use of renewable electricity at the expense of high capital expenditure due to the size of the electrolyzer needed. All these capture and utilization systems are almost three times cheaper than importing green hydrogen for use in aluminium furnaces, a potential solution still under experimental validation in the aluminium sector.

**Keywords**: Aluminium, Decarbonization, Carbon capture, Cost, Emissions.

* 1. Introduction

In 2021, the aluminium sector reported a footprint of around 1.17 billion tonnes of CO2 equivalent, i.e., 2% of global industrial emissions (IAI 2023). Many industries are reliant on the use of aluminium, including but not limited to, aerospace, automotive, beverage can, construction, and renewable energy systems such as solar panels and wind turbines. Secondary aluminium production involves remelting a mixture of scrap and pure aluminium and then rolling it into sheets. This process requires furnaces operating at high temperatures of over 1000°C, the majority of which use fossil based natural gas. While direct electrification could readily provide decarbonization solutions for lower temperature systems; the use of combustible fuels for aluminium remelting furnaces remains the only technically viable solution at large scales. To this end, burning hydrogen fuel is also possible. However, the effect of higher flame temperatures and increased water vapor concentration on product quality are yet to be determined. Hence, a crucial consideration in the industry’s current decarbonization plans is the management strategy of CO2 emissions from burning fossil or synthetic natural gas (SNG). Among the technological solutions for capturing CO2 are oxy-combustion furnaces, conventional amine-based absorption systems, novel membrane units, structured solid sorbents such as metal organic frameworks (MOFs), and cryogenic routes (Zanco et al. 2021). Captured CO2 can then be used to manufacture fuels (SNG) or materials (e.g., plastics), mineralized to produce cement additives (such as CaCO3), or stored in geological formations. Figure 1 presents a graphical illustration of the different alternatives considered in this work. These scenarios were defined by combining multiple capture and utilization technologies of interest to the aluminium industry, resulting in more than 20 feasible configurations. Such analysis calls for a systemic study to evaluate competing technologies based on multiple performance indicators. In this study, a CO2 capture and management strategy is devised for a secondary aluminium production facility, while capitalizing on potential waste heat recovery and system integration opportunities.

A diagram of a factory

Description automatically generated

Figure 1: Potential CCUS routes for decarbonizing secondary aluminium production.

* 1. Methods

An optimization problem for an operating aluminium facility is developed based on minimal incremental costs. Key performance indicators are defined to compare the solutions in terms of thermodynamic, economic, and environmental impact aspects.

* + 1. Aluminium process modelling and description of CCUS systems

Figure 2 illustrates a process flowsheet of the secondary aluminium production facility and the CCUS technologies being evaluated. First, pure aluminium is preheated to 250°C. Subsequently, both pure and scrap aluminium are fed into the melting furnace where they undergo fusion at 660°C, and are superheated to roughly 750°C. Next, the molten aluminium is fed into the direct cast chilling process through the holding furnaces where it solidifies into cast ingots using water as the cooling medium. The ingots are then surface polished in the scalper, annealed at 550°C in pusher furnaces, and rolled into thin sheets. The final treatment step occurs in the annealing continuous line (ACL) where the coils are chemically and thermally treated at approximately 550°C. All plant furnaces emit flue gases containing CO2, that can be captured and utilized using different technologies. Chemical absorption using amine solvents is one option and consumes 3.6 MJsteam/kgCO2 (Flórez-Orrego et al. 2020). Alternatively, temperature-swing adsorption beds filled with metal organic frameworks (MOFs) can reduce steam consumption down to 0.8 MJsteam/kgCO2 (Lin et al. 2021). Other capture technologies relying on electricity, such as cryogenic separation and membranes,consume 1, and 0.4 kWhEE/kg CO2 respectively (Song et al. 2019; Janakiram et al. 2021). In case of oxycombustion, 0.3 kWhEE/kgO2 for air separation is needed (Nascimento Silva, Flórez-Orrego, and De Oliveira Junior 2019).

A diagram of different types of materials

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Figure 2: Secondary aluminium production facility and CCUS alternatives.

* + 1. Optimization problem definition

Osmose Lua platform developed in the IPESE group at EPFL (Yoo et al. 2015) is used to handle the MILP formulation that minimizes the total cost subject to feasibility constraints, shown in equations (1-6). OSMOSE uses solvers supported by ampl® such as CPLEX or CBC. In this study, the size of the MILPs varied depending on the system configuration from 15 to 35 thousand variables subject to 13 to 34 thousand constraints.

(1)

(2)

(3)

(4)

(5)

Assumed energy prices are: natural gas: 0.07 €/kWh; H2: 7 €/kg; electricity: 0.15€/kWh (Jan/Feb/Nov/Dec), 0.001€/kWh (other months); and CO2 tax:120 €/t. Cop1&2 are the fixed and variable operating cost, Cinv1&2 are those of investment cost, qw is the heat load of unit w, R is the heat cascaded from interval r+1 to r, and W is the power import or export. Binary and load factor define the existence and size of the utility units.

* 1. Results and Discussion

Figure 3 presents a high-level summary for the CCUS options under evaluation, and a reference hydrogen case study for comparison. Results indicate that the injection route exhibits the lowest increase in energy load compared to the base case due to the CO2 compression. This is followed by importing hydrogen from the grid as no capture or utilization energy penalty is incurred. Cryogenic and oxyfuel CO2 capture methods for injection have a higher energy load than some mineralization pathways due to the larger electricity penalty required for both technologies. Injection is followed by mineralization, which involves electricity consumption for the pretreatment of the mineral ores. The highest energy loads are observed for methanation followed by olefins production because of the electricity required for producing green hydrogen via electrolysis.



Figure 3: Key performance indicators of competing CCUS options.

Renewability percentage directly reflects the defossilization of aluminium production. The scenario assuming green hydrogen is available in the grid results in the highest renewability of 92 %. This is followed by onsite utilization of captured CO2 for natural gas production using a Swiss electricity mix, which is 77 % renewable. Next is olefins production at approximately 56 %, where the captured CO2 and hydrogen from electrolysis are transformed into olefins with a fuel gas byproduct. Finally, injection and mineralization routes still heavily rely on fossil natural gasimport resulting in the lowest renewability index. Introducing gasification or importing bio-SNG from the grid to these latter scenarios would substantially increase their renewability indices and result in negative overall CO2 emissions.

In terms of capture efficiency, almost all routes achieve an 80% reduction in direct CO2 emissions of the plant. This is lower than efficiencies typically reported for the evaluated capture technologies because of some losses occurring from the plant furnaces during aluminium loading. The capture efficiency of the olefins and methane production routes is slightly lower due to the need for optimized storage systems to supply the plant fuel demands and contain emitted CO2. An important consideration to account for when utilizing electricity grids are the indirect emissions resulting from that electricity. For some scenarios indirect emissions reach up to 150 kgCO2/tAl, surpassing the emissions of the base case and resulting merely in a scope shifting outcome.

Importing green hydrogen at current prices increases operating expenses (OPEX) by up to 3 times compared to the base case. All the CCUS options provide economic benefits in terms of OPEX compared to the base case. The CO2 injection route reduces OPEX due to the avoided CO2 taxes that would be incurred in case emissions continue. The mineralization option also provides a small benefit in operational costs resulting from the value of marketable cement additives. These economic benefits are almost quadrupled in cases of methanation and olefins production due to the higher value of these products compared to simply injecting or mineralizing the captured CO2.

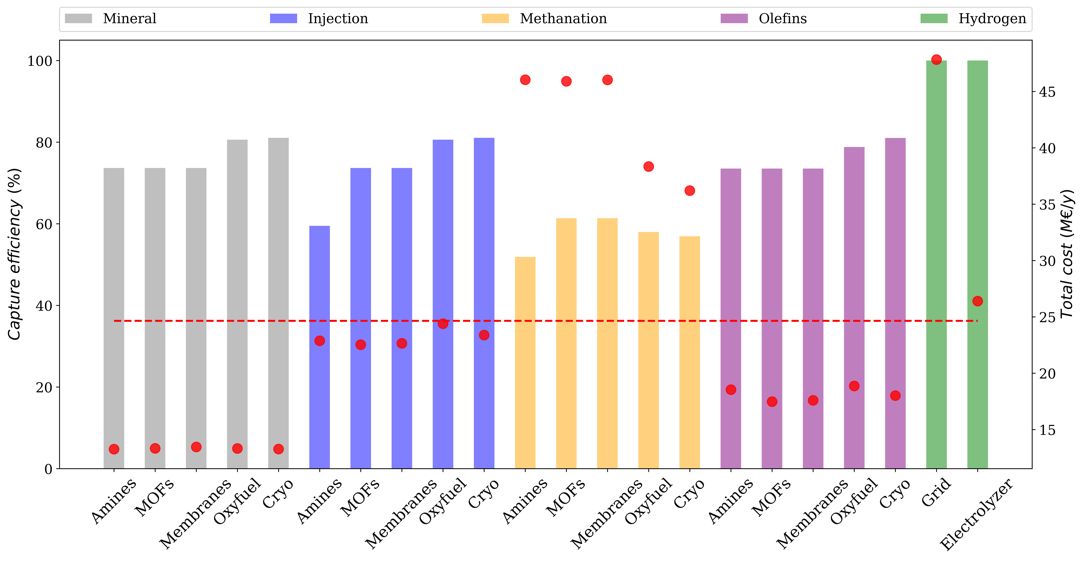


Figure 4: Capture efficiency (left axis, bar plots) and total costs (right axis, red dots) for the CCUS options. Total cost of the base case is indicated with a red dashed line for comparison.

Next, the total annualized costs with relation to capture efficiencies for the evaluated scenarios are presented in Figure 4. Oxyfuel and cryogenic separation almost always achieve the highest capture efficiency, except in the methanation route where additional losses are attributed to storage systems. Mineralization options offer the lowest total cost followed by olefins production due to the added value of products. The total costs of either mineralization, olefin production or injection remain lower than the base case. Methanation is more costly than the base case due to the oversized electrolysis system which needs further optimization. Finally, current green hydrogen prices do not allow economic competition with capture pathways. In this regard, producing hydrogen via electrolysis seems to be more promising. However, technical difficulties summarized in hydrogen storage, higher furnace temperatures, and furnace gas composition currently impede wide application of hydrogen combustion in the aluminium industry.

* 1. Conclusions

In conclusion, several CCUS pathways were evaluated for decarbonizing a secondary aluminium production facility. Up to 80% capture efficiency is reported for the evaluated technologies. It was found that injection and mineralization pathways sustain the lowest energy consumption penalty (20% higher than the base case). However, these options provide the least operational revenue due to the lower income compared to fuels or chemicals produced in the methanation and olefins routes. In addition, monitoring the indirect emissions of the utilized electricity is crucial for maximizing decarbonization potential and avoiding any scope shifting effects. Complete defossilization is possible if such capture pathways are coupled with the use of renewable electricity. Negative CO2 emissions are also achievable if SNG of biogenic origin is used in the plant, captured, and transformed via any of the identified utilization options. Finally, burning green hydrogen remains a viable but challenging alternative in both technical and economic aspects compared to the presented capture, storage, and utilization options.

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