Multi-Period, Enterprise-Scale Optimisation Framework for Cost-Effective Decarbonisation of Aluminium Manufacturing

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Abstract

Aluminium manufacturing faces significant decarbonisation challenges, including due to its high demand for electricity, supply of which must be continuous and reliable. Electricity may account for over 40 % of total operational costs aside from raw materials expense, therefore, access to low-cost and reliable electricity becomes a critical enabler for economic sustainability of aluminium smelters. As industries globally strive to meet net-zero carbon emissions and increase their demand for, sustainable production methods which balance cost efficiency, operational reliability, and emissions reduction will be essential for the aluminium industry's own decarbonisation. This study presents a multi-period 'least-cost' optimisation framework, tailored for meeting electricity demand of an aluminium smelter through a customised supply mix, integrating several renewable and conventional generation technologies, storage solutions, and carbon capture, such that a defined decarbonisation target is met.

The objective function for the optimisation routine is to minimise the levelized cost of electricity (LCOE) while meeting the defined decarbonisation target and ensuring the electricity demand is met during all hours of the year through a mix of various generation and storage sources. To accurately estimate the LCOE, the work incorporates a robust financial model which captures the cost of various technologies in the mix such as - capital expenditure of equipment and supporting infrastructure, fixed operational expenditure to maintain and operate the energy system and variable operational expenditure such as fuel cost and efficiency corresponding to each technology. The LCOE is designed to additionally account for any electricity emissions cost from conventional sources because of carbon tax on electricity emissions in the country of focus. The optimisation tool in such cases would propose a supply mix that minimises the overall effective electricity cost, including emissions cost of any smelter. The technical and operational characteristics of the technologies (gas turbines, solar photovoltaics, wind, hydropower, hydrogen, nuclear, battery energy storage systems, long-duration energy storage, and carbon capture) have also been carefully modelled with configurable parameters to support scenario analysis.

Our early results demonstrate that a hybrid energy mix including renewables and storage can significantly reduce emissions while still maintaining economic feasibility. Analysis specific to UAE suggests solar photovoltaic (PV) with storage playing a dominant role in this energy transition for aluminium smelting due to high irradiance levels in this region.

Keywords: Decarbonisation, Aluminium smelting, Electricity mix optimisation, Renewable energy, Energy storage

1. Context and Present Situation

To address the pressing challenges of climate change and meet global emissions reduction targets it is imperative for hard-to-abate sectors such as aluminium manufacturing to transition to sustainable energy systems.

Aluminium production is an energy-intensive process, with approximately 65 % global average [1, p. 14] of its total emissions coming from fossil fuel generated electricity consumption. Aluminium metal is often regarded as solid electricity storage. This is particularly true for the Hall-Héroult process, the primary method for smelting aluminium, which requires large amounts of electricity to convert alumina into pure aluminium. The process demands continuous and stable supply of electricity to ensure efficient operations, meaning that any power disruptions can cause significant production delays and equipment damage, resulting in costly downtime and repairs.

Furthermore, as economic returns in aluminium production are highly volatile as a result of being tied to the market prices, minimizing operating cost becomes critical to ensure economic viability of a project. As electricity may account for over 40 % of total operational costs, depending on electricity price, aside from raw material expenses, therefore, access to low-cost power is critical to ensure economic viability of a smelter.

2. Current Market Challenges

The need for reliable and low-cost power for aluminium production has traditionally led to the use of fossil fuels or hydropower.

As industries globally strive to meet net-zero carbon emission targets, the aluminium sector faces the dual challenge of maintaining cost efficiency while reducing its carbon footprint. Further, as the demand for aluminium continues to grow globally, spurred by its applications in transportation, construction, and renewable energy technologies, the need for sustainable production methods will only become more critical in the future.

Addressing these challenges requires systematic optimisation of the energy generation mix to achieve a balance between cost efficiency, reliability, and emission reduction. This would involve integrating renewable energy technologies, deploying advanced energy storage systems, and leveraging carbon capture and utilisation solutions to reduce the carbon footprint while ensuring reliability and economic viability.

To determine an optimised energy generation-mix customised for the smelter design, requirements, and location, aluminium manufacturers could adopt advanced modelling techniques to navigate through these complex challenges. This study explores one such opportunity by formulating and solving a comprehensive electricity optimisation problem tailored to the unique requirements of aluminium manufacturing, aiming to pave the way for a more sustainable and efficient industry.

3. State of the Art

Aluminium manufacturing, as one of the most electricity-intensive industries, has become a testbed for multi-period, multi-objective optimisation models aimed at minimizing both energy costs and emissions. Recent studies, such as Sgouridis et al. [2], use linear programming to determine optimal combinations of grid, on-site renewables, and storage, factoring in load flexibility and long-term investments. Multi-objective approaches, like those by De Maigret et al. [3], reveal the trade-off curve (Pareto front) between cost and carbon emissions, showing that integrating renewable and low-carbon generation technologies, advanced storage solutions, and CCU systems, the model achieved significant cost savings and emission reductions. The key contributions include the multi-period, mixed-integer optimization developed capturing the operational and economic characteristics of various energy technologies. The model demonstrated how industries can achieve ambitious decarbonisation targets without compromising operational reliability. The results presented in this paper provide actionable insights for policymakers, energy planners, and industry stakeholders, paving the way for sustainable and economically viable energy transitions.

6.2 Future Directions

The study highlights several areas for future research. Some of the key directions are listed below.

Stochastic Modeling: Incorporating uncertainties in renewable energy availability, demand fluctuations, and market prices can improve the robustness of the optimization results.

Dynamic Policy Constraints: Future work could explore the impact of dynamic carbon taxes, subsidies, and other regulatory measures.

Emerging Technologies: Integrating next-generation technologies, such as advanced hydrogen-based systems or modular nuclear reactors, into the optimization framework.

Industry-Specific Applications: Adapting the model to other high-emission industries to broaden its applicability.

7. References

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