Electricity Market-Driven Optimisation of Aluminium Smelting Operations

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Abstract

The increasing integration of volatile renewable energy sources (VRES) into electricity grids presents challenges and opportunities for the energy-intensive aluminium smelting industry. Traditionally, smelter operations have been optimised for intrinsic electrolysis efficiency under stable, long-term electricity supply contracts that do not account for grid volatility. However, with rising VRES penetration, optimal smelter profitability and efficiency now require a system-level approach that incorporates demand-side flexibility.

This study evaluates the flexibility potential of primary aluminium smelters by analysing four years of electricity market data across six European smelter locations. A plant energy conservation model is developed and coupled with a linear optimisation algorithm to determine profit-maximising production schedules while preserving the stability of the Hall-Héroult electrolysis process. Our modelling accounts for the physical inertia of the Hall-Héroult process, including its sensitivity to heat balance and electrolyte composition, and demonstrates conditional feasibility of load modulation within narrow thermal stability bounds.

We show that flexible smelter operation—supported by advances in process control, real-time electrolyte state monitoring, and energy-aware scheduling—can unlock significant value by leveraging off-peak electricity prices, enhancing grid stability, and supporting renewable integration. Aluminium smelters, with their immense electricity demand and high opportunity costs of load curtailment, are uniquely positioned to act as responsive grid participants rather than static base-load consumers.

To mitigate operational and market risks, we propose a dual-power procurement strategy: a base-load supply secured via long-term power purchase agreements, complemented by flexible spot-market procurement. Our findings call for a paradigm shift in aluminium electrolysis process engineering—integrating electricity market participation into smelter operation design—and offer actionable insights for engineers, policymakers, and energy market operators navigating the era of renewable-dominated grids.

Keywords: Demand flexibility, Electrolysis energy efficiency, Electricity markets.

1. Introduction

The global rise in variable renewable energy sources (VRES), such as wind and solar, is reshaping electricity markets, introducing both opportunities and operational challenges for energy-intensive industries. In 2024, global electricity demand grew by 4.3 %, with Europe reversing a multi-year decline. Despite record renewable penetration, CO_2 emissions reached a new high of 37.8 Gt, underscoring the urgency of systemic decarbonisation [1].

As VRES become dominant in supply, power systems are increasingly characterised by extreme price volatility—including near-zero prices during renewable surpluses and sharp scarcity prices during deficits [2]. In this context, demand-side flexibility is recognised as a key mechanism for balancing supply and demand, moderating prices, and improving grid resilience. Brown et al. show that even modest elasticity in aggregate demand can substantially reduce price volatility [3]. However, their models abstract away from the operational constraints that real-world industrial processes impose.

Traditionally, primary aluminium smelters have been operated as fixed base-load consumers, with optimisation focused on intrinsic current efficiency in the Hall-Héroult process under stable long-term electricity contracts [4]. This model inherently resists dynamic modulation due to the thermal inertia of the electrolytic bath and the chemical lag in alumina concentration adjustment. Excessive load reduction risks cryolite freezing, sludge buildup, and anode effects, making stability a paramount concern.

Sævarsdóttir et al. suggest that controlled short-duration modulations are feasible without compromising cell integrity, provided that thermal and chemical boundaries are respected [5]. These findings ground our approach in engineering reality: flexibility is conditionally achievable, not merely economic theory.

Meanwhile, digital instrumentation and advanced process control offer new levers for operational adaptability. Recent work by Sævarsdóttir & Kvande highlight innovations such as real-time bath chemistry sensing and predictive control, which are critical for enabling responsiveness [6]. We argue that aluminium smelters—given their massive loads and calculable opportunity costs—are uniquely suited to act as responsive resources in zero-carbon electricity markets [2].

This study investigates the potential of aluminium smelters to provide flexible demand response through energy-aware operational optimisation. We present a plant energy model integrated with electricity market dynamics across six European regions, exploring a hybrid power procurement approach: combining deterministic power from long-term agreements with market-exposed volumes for flexibility. This paradigm shift reframes the smelter not just as a consumer, but as a partner in the transition to a renewable-powered grid.

2. Flexible Smelting Operations

To investigate the economic potential of primary aluminium smelters in VRES-dominated electricity markets, we introduce a simple yet insightful energy-based model that optimises production rates while ensuring operational stability. Unlike traditional smelter operations at fixed output, our model enables dynamic adjustment of electricity consumption to align with fluctuating energy prices, capitalising on low-cost periods driven by wind and solar power. Real-world experimentation, such as small-scale power modulation studies [7], demonstrates the feasibility of adjusting smelter operations to support grid stability, inspiring our approach to explore deeper fluctuations. By allowing production rates to vary up to 60 % of nominal capacity, our model explores an end-to-end optimisation of smelter operations and electricity grid interactions, delivering significant financial benefits without violating energy conservation principles.

Our model represents the smelter as an energy system with two core components: an electrical circuit and a thermal balance framework. The electrical circuit captures the direct current (DC) power needed for the smelting process, which converts alumina into aluminium through electrolysis. Power consumption is adjusted by varying the current input, directly influencing production rates. For instance, reducing current by up to 50 % lowers output during high electricity prices, while increasing current during low-price periods maximises production.

The thermal balance framework ensures Hall-Héroult cell stability by managing heat input from electrical resistance (Joule heating) against losses, with approximately 40 % of heat escaping

Looking ahead, the role of industrial flexibility will only grow. The rise of hyperscale data centre demand, the continued integration of variable renewables, and tightening carbon policy all point toward a future electricity system that rewards responsiveness and penalizes rigidity.

Demand-side flexibility is rapidly becoming a core asset in electricity systems. Smelters that can act as adaptive loads – not just base-load consumers – gain a competitive edge while supporting renewable integration and price stability. However, scaling this approach requires aligned market access, regulatory support, and technical readiness. Grid operators, market designers, and aluminium producers must collaborate to accelerate deployment. Pilot programs in high-volatility regions – with robust modern instrumentation and price transparency – should be prioritized to demonstrate feasibility and derisk investment.

Smelter flexibility is no longer a speculative innovation. It is a strategic imperative for competitiveness in a decarbonizing grid.

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9. References

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