

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, CO₂ 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—were 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

through off-gas at 300 °C and 50 % through cell shell surfaces. Thermal reservoirs, such as the cryolite bath and refractory lining, buffer temperature fluctuations during current reductions, maintaining superheat to prevent process disruptions. Our model enforces energy conservation by balancing power input with production and heat losses, ensuring physical viability even at aggressive modulation depths.

To estimate financial impacts, we couple the model with a linear optimisation solver that determines hourly production rates maximising revenue across six European smelter locations from 2021 to 2024. The solver uses electricity market data, featuring volatile prices driven by VRES, to schedule high production during near-zero price periods and low production during scarcity spikes. Profit is calculated as the difference between aluminium sales and electricity, materials, labour and maintenance costs, constrained by minimum current thresholds to preserve cell stability and thermal equilibrium to avoid ledge formation. This approach transforms smelters from inflexible, base-load consumers into agile participants in VRES markets, contributing to grid stability and price formation, as described by the flex-demand-meritorder [3]. By optimising production to exploit price volatility, smelters unlock substantial economic value, potentially decreasing electricity cost while maintaining annual revenue, i.e., over 1000 USD/t Al savings compared to fixed operations. While achieving such deep modulation requires overcoming significant technical challenges, discussed in a later section, our model demonstrates the financial promise of flexible smelting, paving the way for a new era of plant-grid synergy.

3. Energy-Based Model for Flexible Smelter Operations

To quantify the economic value of demand-side flexibility in aluminium smelting, we developed a deterministic, energy-based optimisation model that adjusts production rates in response to hourly electricity prices while maintaining operational stability. The model aims to capture the essential dynamics of a smelting facility without introducing unnecessary complexity, allowing for transparent evaluation across diverse electricity markets.

3.1 Energy System Representation

The aluminium smelter is represented as a coupled thermal-electrical system operating at hourly resolution. At each time step t , the decision variable is the aluminium production rate q_t (kg/h), which governs total electricity demand through a decomposition into load-dependent and load-independent components.

The minimum specific energy demand per kilogram of aluminium, denoted as E_{esp} and set at 12 kWh/kg, is decomposed into two components: a fixed baseline related to maintaining thermal stability and a variable component associated with electrolysis and heat losses proportional to production. Accordingly, we express E_{esp} by two additive terms:

$$E_{esp} = e_{dynamic} + e_{baseline} = 12 \text{ kWh/kg} \quad (1)$$

where:

- $e_{dynamic}$ Models the specific energy requirement per kilogram of aluminium that scales with the production rate, comprising the electrochemical minimum and production-proportional thermal losses
- $e_{baseline}$ Denotes the fixed specific thermal energy required to maintain cell temperature stability at nominal capacity

The electrochemical foundation of $e_{dynamic}$ lies in the theoretical minimum energy needed to reduce alumina to aluminium, derived from Faraday's law and assuming a reversible cell voltage of

approximately 1.2 V. This yields a lower-bound specific energy demand of ~3.6 kWh/kg, here denoted $e_{Faraday}$.

$$e_{dynamic} = e_{Faraday} + e_{heat,dynamic} \approx 7 \text{ kWh/kg} \quad (2)$$

As noted in Section 2 and supported by thermodynamic and electrochemical literature [8, 9], a substantial fraction of these thermal losses, estimated at 40 %, originates from gas-evolving reactions at the anode. These mechanisms scale with current density and reaction velocity, and are thermodynamically linked to local entropy effects and boundary-layer disruption. Solheim [8] quantifies a heat deficit of ~8.5 kW/m² at the anode due to gas evolution, while Sequeira et al. [9] demonstrate how bubble formation enhances convective energy transfer. These insights validate the proportional treatment of gas-phase heat loss in the model formulation.

The total electricity consumption per hour is directly proportional to the production rate:

$$E_t = q_t * e_{dynamic} + Q_{nominal} * e_{baseline} \quad (3)$$

where:

E_t : electricity consumption in hour t, kWh

$Q_{nominal}$: plant nominal production rate, kg/h

$e_{baseline}$: fixed specific thermal energy demand, 5 kWh/kg

The second term reflects a modeled baseline thermal load required to maintain operational stability, independent of production output. While the model treats this term as fixed for tractability, real-world implementations may deploy dynamic thermal management strategies—such as adaptive insulation control or sidewall heat extraction—to reduce thermal energy requirements and preserve the heat balance under fluctuating energy input. Such techniques can help maintain side ledge integrity and extend cell lifespan, complementing the broader goals of flexible, grid-responsive operation.

$$E_{eff}(t) = E_t/q_t = e_{dynamic} + e_{baseline}(Q_{nominal}/q_t) \quad (4)$$

This function increases as production decreases—a result that challenges conventional engineering intuition. Historically, minimizing $E_{eff}(t)$ has been treated as a proxy for plant efficiency. However, this model reveals that lower throughput may yield higher specific energy due to fixed thermal loads, and that this is not inherently suboptimal.

In modern electricity markets, cost-optimal smelter operation must consider system-wide objectives. During periods of grid stress or high pricing, curtailing production—even at the cost of higher $E_{eff}(t)$ —may provide economic and environmental advantages that outweigh internal efficiency losses. This reframes the smelter not as a static energy sink, but as a flexible, market-responsive actor within a decarbonizing grid.

To support this operational flexibility, the model incorporates a dual-sourcing electricity procurement strategy:

- A baseload tranche, purchased via long-term power purchase agreements (PPAs), and
- A flexible tranche, priced in real time via day-ahead market mechanisms

This hybrid architecture allows the model to explore flexible smelting strategies that respond dynamically to price signals while maintaining core thermal stability requirements.

3.2 Operational Constraints and Stability Enforcement

Smelter operations are bounded by technical constraints designed to reflect electrolysis process requirements:

- Minimum production rate: $Q_{min} = 0.4 \cdot Q_{nominal}$
- Maximum production rate: $Q_{max} = 1.05 \cdot Q_{nominal}$
- Ramp rate constraint: $q_t - q_{t-1} \leq \Delta q_{max}$

These constraints enforce quasi-continuity in production profiles and serve as engineering proxies for thermal stability and control system limitations.

3.3 Cost Structure and Profit Maximisation

Total profit Π is computed as the difference between revenue from aluminium sales and the costs of electricity and smelter operations:

$$\Pi = \sum_t R_t(q_t) - C_t(q_t) \quad (5)$$

where:

$$R_t(q_t) = q_t \cdot Al_{price} \quad (6)$$

$$C_t(q_t) = q_t \cdot (e_{dynamic} \cdot El.Price_t + C_{material} + C_{emissions}) + C_{fix} \quad (7)$$

The optimisation is implemented using the PuLP linear programming library in Python. The solver determines hourly production rates q_t that maximise total profit over one calendar year, given fixed aluminium prices and historical day-ahead electricity prices.

3.4 Application Scope

The model is applied to six representative European smelter zones using 2021–2024 market data. Regional differentiation is preserved through:

- Zonal electricity prices (sourced from Fraunhofer ISE Energy Charts) [10]
- Grid carbon intensity historical data from Electricity Maps [11]
- Currency exchange normalisation (e.g., EUR to USD)
- Uniform plant specifications for comparability

Results illustrate how optimised flexibility strategies improve economic outcomes by synchronising smelter demand with VRES-driven price signals—unlocking value from grid volatility while preserving the physical viability of Hall-Héroult operations.

4. Electricity Markets Architecture and Outlook

The electricity market is evolving rapidly, shaped by volatility, demand shocks, and a shift toward renewable dominance. This section examines the procurement logic applied in our model, grounded in recent price behaviour, and expands the analysis to include emerging trends, such as hyperscale AI demand and the economic implications of variable renewables. In this context, flexible aluminium smelting becomes not just efficient, but essential.

4.1 Context and Design Objectives

The model employs a hybrid electricity procurement strategy that blends fixed bilateral contracts with spot market sourcing. This dual approach balances operational security with price

responsiveness, enabling the smelter to adapt dynamically to market conditions without compromising core stability.

Figures 1 and 2 illustrate recent European electricity price patterns, emphasizing the frequency and depth of price troughs that flexible consumers can exploit. Complementing this, Table 1 provides a pivot-style breakdown across multiple market zones, capturing three key price features: intraday volatility (Table 1a), prevalence of near-zero prices (1b), and the frequency of price spikes above 0.20 USD/kWh (1c). Together, these indicators frame the tactical environment in which load shaping delivers value.

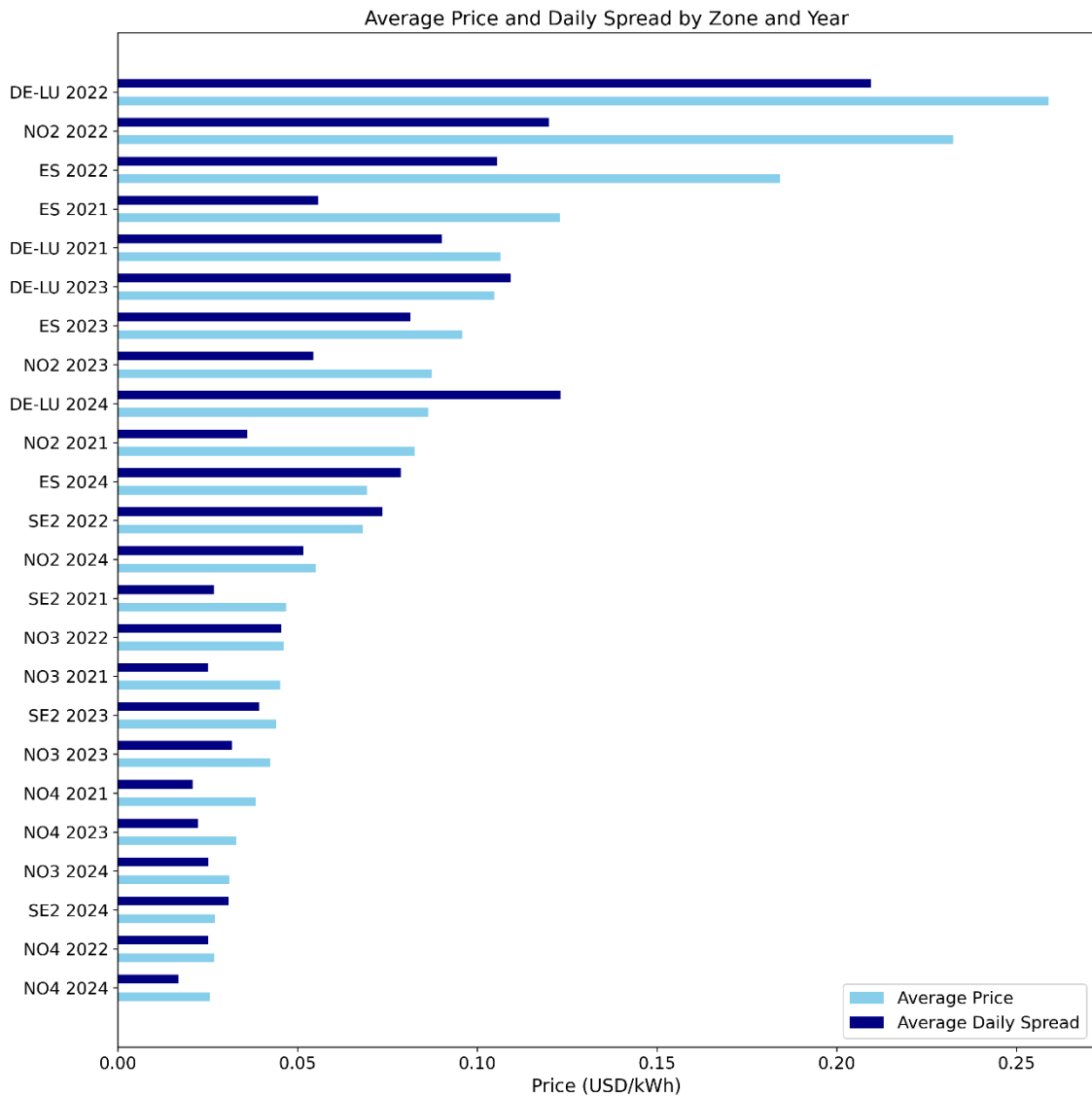


Figure 1. Bar chart showing average price and average daily spread by zone-year.

This empirical backdrop not only reflects historical volatility—it foreshadows more turbulent dynamics as carbon-free generation grows. In this context, demand-side flexibility is no longer a secondary optimization; it becomes a strategic imperative. Aluminium smelters positioned to respond to real-time signals are better equipped to manage procurement risks and contribute to grid efficiency in a decarbonizing world.

4.2 Shifting Demand Landscape and Structural Pressures

The electricity grid is undergoing not only a transformation on the generation side—with growing renewable penetration and decentralized resources—but also on the demand side, where new industrial-scale consumers are reshaping the baseload landscape. Among these, hyperscale AI data centers are emerging as a dominant load class. The IEA’s Global Energy Review 2025 identifies data center and artificial intelligence applications as major contributors to recent electricity demand growth [1]. Deployments approaching 10 GW of capacity are now under active planning and construction, rivaling or exceeding the scale of many national industrial demands.

Unlike traditional industrial loads, these AI facilities have high uptime requirements, deep pockets, and a willingness to pay premium prices to secure uninterrupted access to clean, dispatchable power. This competitive posture is expected to put persistent upward pressure on average electricity prices, particularly during baseload intervals, effectively redefining the economic environment in which traditional energy-intensive industries such as aluminium smelting operate.

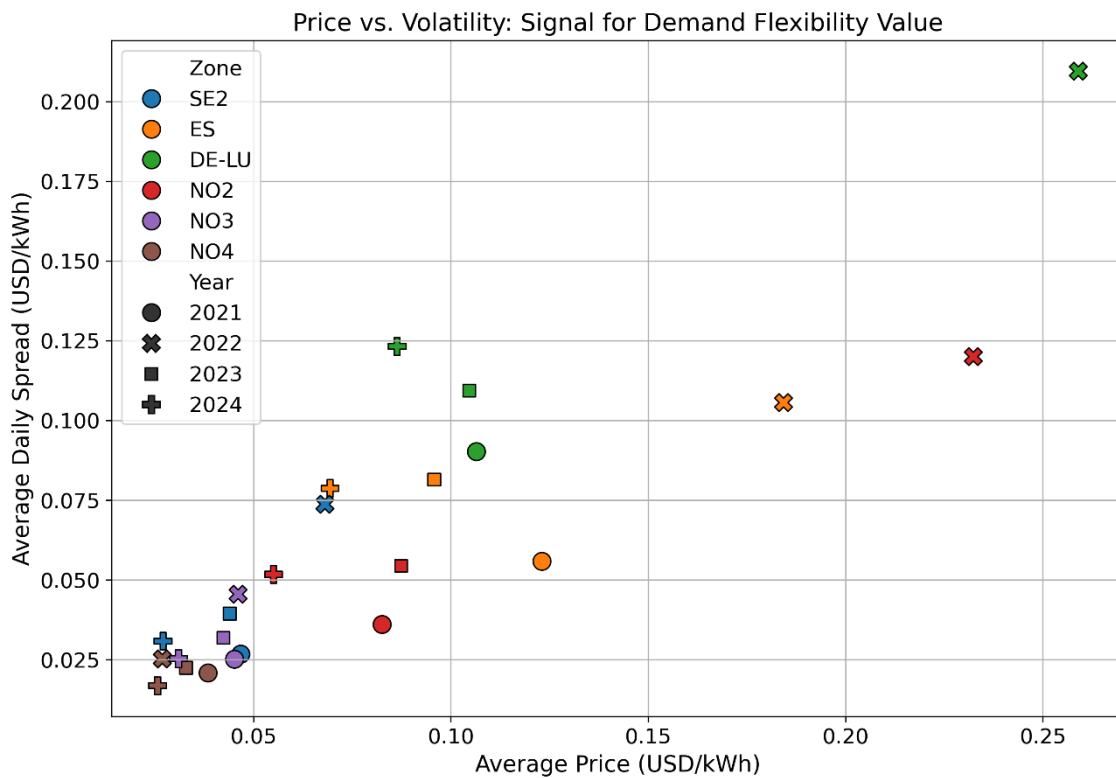


Figure 2. Scatter plot showing average price vs. average daily spread, decorated by zone and year.

Moreover, these data centers depend on advanced semiconductors, whose own manufacturing processes are exceptionally energy-intensive. This creates a feedback loop between demand growth and energy system burden—one that is not merely economic but increasingly strategic. Amid geopolitical instability and growing concerns over supply chain sovereignty, national priorities are accelerating energy infrastructure expansion oriented around digital and technological security, not just economic efficiency. As a result, inflexible industrial assets may find themselves in structurally disadvantaged positions if they cannot adapt to this new dispatch context.

Table 1. Summary of electricity market characteristics by zone and year.**(a) Volatility Ratio (%): Daily price spread as a share of average price.**

Zone	2021	2022	2023	2024
DE-LU	84.7	80.9	104.4	142.6
ES	45.3	57.3	85.0	113.4
NO2	43.6	51.6	62.2	93.8
NO3	55.5	98.7	75.0	81.6
NO4	54.0	93.7	68.1	65.4
SE2	57.1	108.2	89.5	113.7

(b) Share of Hours with Prices Below USD 0.01/kWh: Low-cost operations opportunity.

Zone	2021	2022	2023	2024
DE-LU	3.13	2.16	7.19	9.61
ES	3.05	1.45	6.88	21.37
NO2	0.66	1.24	5.63	6.31
NO3	1.76	20.7	16.4	20.64
NO4	1.74	24.12	16.1	23.13
SE2	2.35	9.57	18.2	36.6

(c) Share of Hours with Prices Above USD 0.20/kWh: Exposure to scarcity pricing.

Zone	2021	2022	2023	2024
DE-LU	12.12	60.9	2.76	1.99
ES	19.52	38.28	0.26	0.02
NO2	3.14	49.5	0.82	0.5
NO3	0.71	5.17	0.23	0.16
NO4	0.71	1.46	0.22	0.00
SE2	0.76	8.92	0.27	0.16

4.3 Renewable Penetration and Capture Economics

In parallel, variable renewable energy (VRE) sources—particularly wind and solar—continue to expand their share in global electricity systems. Thanks to abundant solar energy, these resources come with zero marginal costs, a fact that pushes average market prices downward. However, the economics of VRE adoption are increasingly constrained not by generation potential, but by the capture price—the actual price VRE producers receive, which can be heavily suppressed during times of surplus.

In this context, flexible demand becomes a system enabler. Smelters capable of temporally shifting load in response to real-time price signals provide a dual benefit: they reduce exposure to unfavorable prices while also supporting VRE deployment by improving overall grid absorption capacity. By shifting consumption to periods of high VRE output, smelters help stabilize prices and increase the realized value of renewable assets, thus contributing to broader decarbonization and grid efficiency goals.

4.4 Dual-Source Procurement Mechanism

The procurement logic integrates a dual-source strategy: fixed bilateral contracts provide operational stability, while dynamic market-based sourcing introduces responsiveness. This architecture allows the smelter to curtail operations when spot prices exceed defined thresholds and to ramp up production when prices are favorable. Threshold calibration is informed by plant-specific cost structures, energy-efficiency trade-offs, and the evolving volatility of electricity markets.

By aligning procurement strategy with macro-level shifts in the electricity landscape, the model positions aluminium smelting as both a responsive market actor and a strategic load-flexibility asset—capable of mitigating systemic stress while improving its own economic performance.

5. Results: Cost Structures, Profit Gains, and Sourcing Strategy

Dynamic electricity pricing unlocks new value streams for aluminium smelters – but only if operations can be adapted to exploit them. This section evaluates how flexible procurement and production strategies reshape smelter economics. Through three complementary visuals, we analyze cost composition, profit differentials, and energy sourcing behavior for each scenario and site.

We simulate optimised plant performance at six European locations using 2021–2024 day-ahead price data, integrating technical constraints and procurement strategy. The results demonstrate how operational agility enhances profitability, reduces exposure to price spikes, and aligns with broader grid efficiency goals. As described in Section 3.3, revenue is calculated from aluminium output, while operational costs included electricity, labour, maintenance, and materials. The model preserved thermal constraints inherent to the Hall-Héroult process and ensured feasible modulation without risking cell integrity.

5.1 Comparative Profitability and Operational Profiles

Figure 3 presents the plant-level profit improvements and unit electricity savings enabled by dynamic operation. Each bar shows the total annual profit under the optimised schedule, while the red line indicates cost savings per tonne of aluminium.

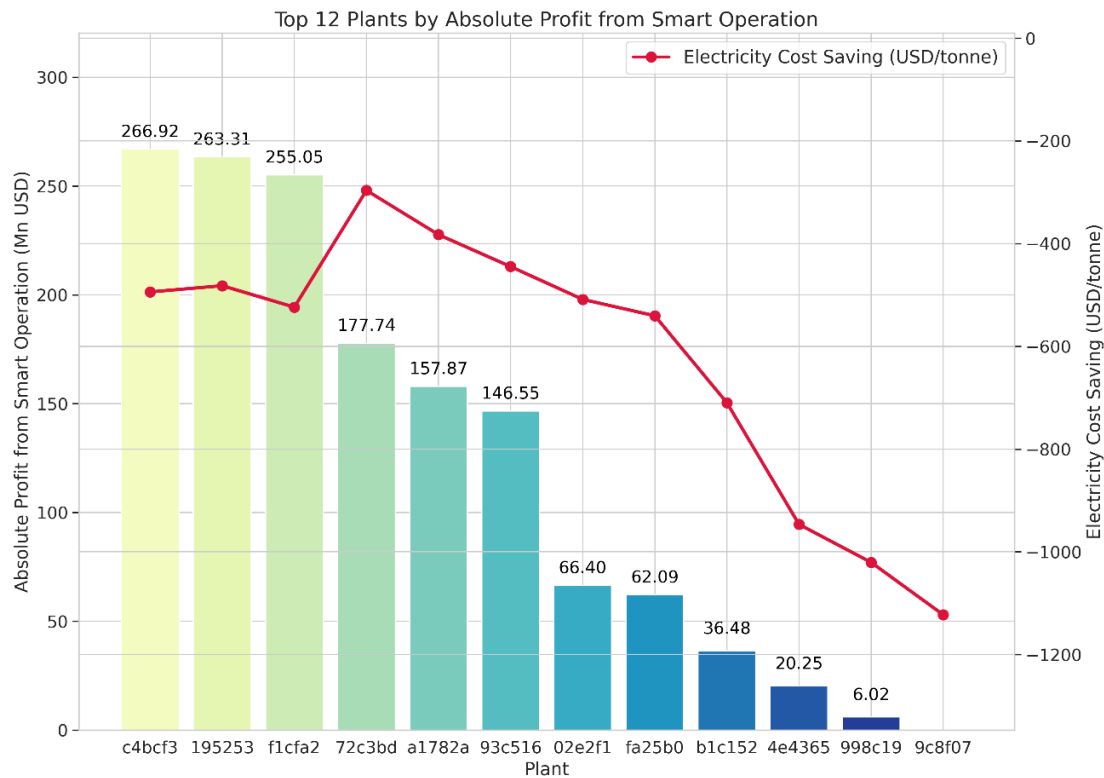


Figure 3. Absolute profit from smart operation (bars) and electricity cost savings per tonne (line) for the top 12 performing smelters (identified by a hash code above).

This visualisation highlights how both plant scale and market conditions influence economic outcomes. It sets the stage for the deeper operational analyses in Figures 4 and 5.

Dynamic vs. Baseload Production: Daily Financial Overview

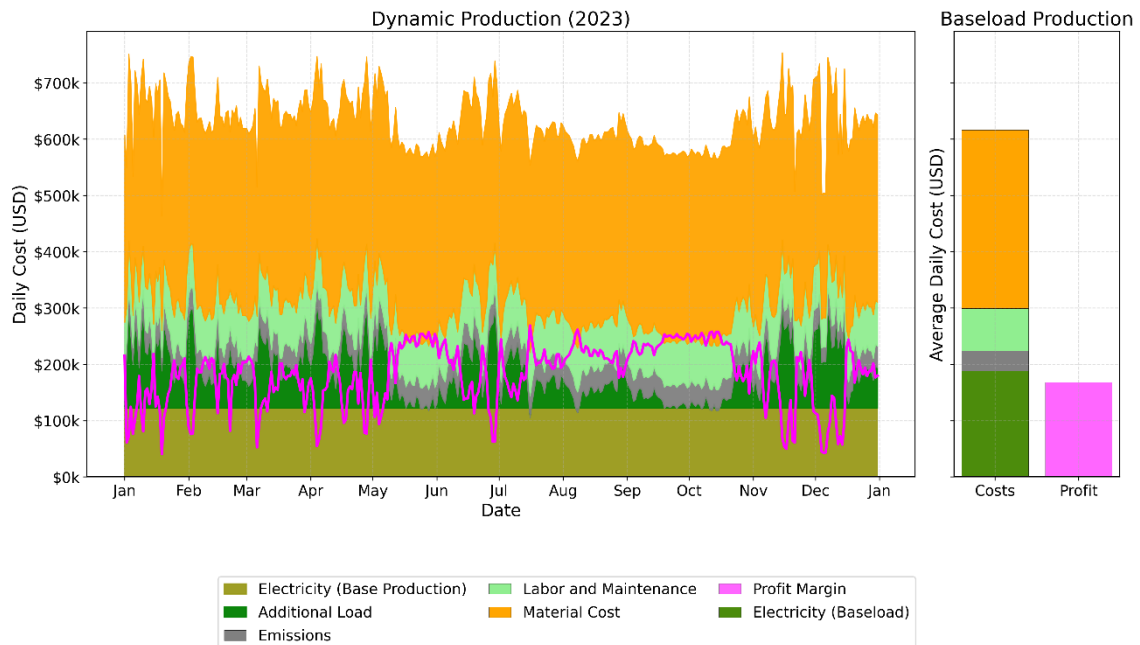


Figure 4. Daily costs and profit of plant A. Left: under dynamic production, Right: versus baseload production. Average profit gain: 15 400 USD/day.

Dynamic vs. Baseload Production: Daily Financial Overview

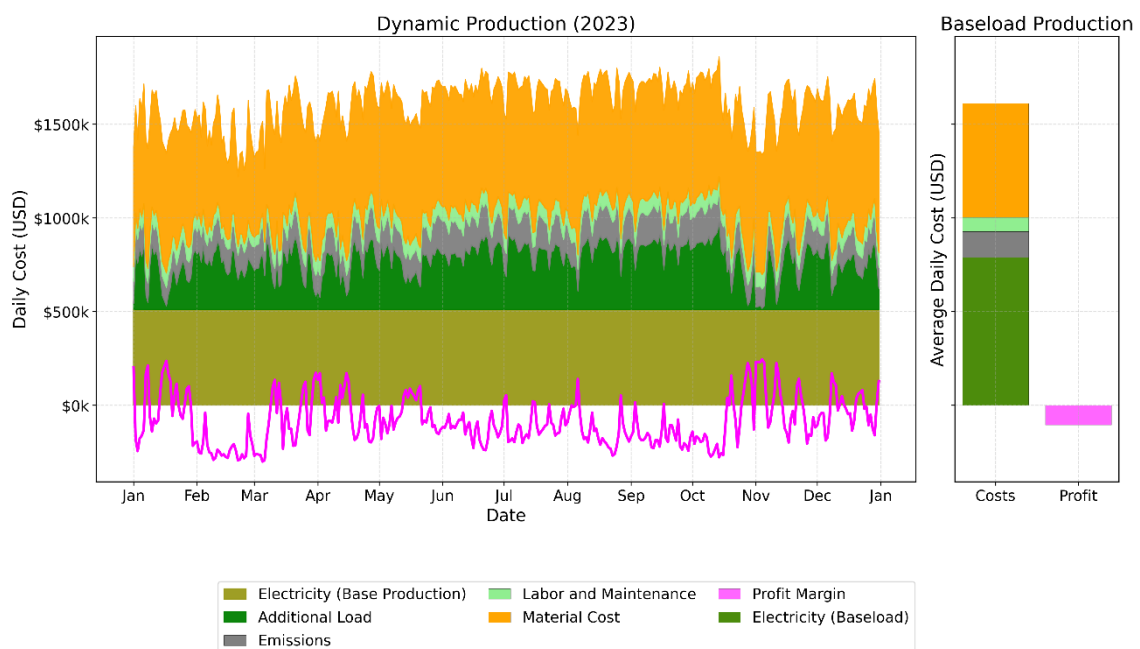


Figure 5. Daily costs and profit of plant B. Left: under dynamic production, Right: versus baseload production. Average profit gain: 62 100 USD/day.

Figures 4 and 5 illustrate the financial and operational impacts of smart operation at two distinct sites: Plant A and Plant B. Plant A demonstrates moderate price responsiveness within a stable, hydropower-rich region. In contrast, Plant B is situated in a highly volatile market, yielding deeper modulation in electricity use and profit variability. In both cases, dynamic control results in meaningful electricity cost savings while preserving annual production viability.

5.2 Remaining Challenges

While the model confirms clear benefits to flexible operation, practical challenges remain. Real-time control of electrochemical stability under frequent modulation is complex, requiring high-resolution instrumentation and robust predictive logic. Market access also varies by geography and regulatory maturity. Not all smelters currently have access to real-time pricing or aggregation mechanisms that would enable dynamic participation.

Finally, the economic feasibility of retrofitting older smelting lines with the necessary sensors and control logic may depend on future electricity price volatility and regulatory incentives. These challenges, however, are not structural limits. They are transitional barriers that can be addressed through targeted investments and policy support, especially as flexibility becomes a grid-critical capability.

6. Enabling Technologies and Market Instruments

Aluminium electrolysis is fundamentally resistant to frequent power modulation due to the heat and chemical inertia of Hall-Héroult cells. Nonetheless, technological progress is enabling increased responsiveness to electricity market signals while preserving operational stability. This section outlines the most critical enablers and discusses remaining technical barriers.

6.1 Enabling Observability for Dynamic Operation

Recent advances in cell instrumentation and process observability have laid the technical foundation for dynamic aluminium smelting. High-resolution sensing of electrochemical conditions is becoming increasingly feasible. For example, Shi et al. demonstrated that individual anode current monitoring systems can resolve the distribution of current across anodes, providing insight into localized cell behaviour and internal states [12]. Complementary work by Mattioni et al. introduced a local observer capable of estimating alumina concentration and anode-cathode distance (ACD) solely from current data, eliminating the need for intrusive physical probes [13].

This emergent observability is a necessary precursor to stable modulation. Traditional base-load operation minimized the need for fine-grained sensing, but flexible operation requires operators to manage more volatile states while preserving superheat, alumina saturation, and ACD within narrow safety margins. Experimental work by Ismail et al. has shown that daily power modulation can be implemented without breaching thermal stability thresholds, provided it remains within defined operating limits [7]. Crucially, Solheim [14] argues—based on cell modelling and operational physics—that maintaining uniform alumina concentration and consistent anode-cathode distance (ACD) is not merely desirable but essential for safe, stable electrolysis. Under modulated operation, fluctuations in energy input can amplify internal imbalances unless such parameters are tightly regulated. These insights reinforce our reliance on sensing and control infrastructure as foundational enablers of flexibility. These combined developments in sensing and control validate key operational assumptions in this study and strengthen the case for market-integrated smelter flexibility.

6.2 Smelter-Level Profitability and System-Wide Value

The economic results outlined in Section 5 confirm the business case for integrating flexible aluminium smelting into electricity markets. By enabling selective curtailment during high-price periods and ramping up production when prices are favourable, smelters can enhance profit margins and reduce procurement risk. These private gains also generate system-wide value.

Beyond firm-level gains, this flexibility generates positive externalities at the system level. By aligning load profiles with renewable generation patterns, smelters help absorb surplus electricity during low-price intervals and reduce stress during peak demand. This not only improves market efficiency but also increases the capture price for variable renewable energy (VRE) producers, accelerating their deployment. In this sense, industrial demand-side response is not merely a private optimization strategy but a public good, reinforcing grid stability and decarbonization objectives [1].

6.3 Implications for Model Deployment and Industrial Feasibility

Efforts like those documented by Ismail et al. are validating models of cell thermal balance under daily power modulation [7]. These studies provide confidence that, under proper constraints, energy input can be varied without violating safety margins. Such experimental validations support our assumptions regarding modulation depth and stability thresholds. However, the ability to generalise these findings to commercial-scale plants still hinges on the availability of precise, high-resolution thermal and electrical monitoring infrastructure.

Beyond process-level feasibility, the model itself incorporates simplifying assumptions to isolate strategic and economic behaviour. Electricity prices are treated deterministically, without accounting for real-time forecast uncertainty. Operational constraints such as ramp-rate limits and minimum downtime are abstracted. Additionally, the smelter is considered in isolation from broader grid balancing mechanisms and ancillary service interactions. While these abstractions allow clarity in evaluating procurement logic and energy efficiency trade-offs, future implementations must account for these complexities to ensure robustness in deployment.

6.4 Policy and Market Design Alignment

Unlocking smelter flexibility at scale requires aligned incentives in electricity markets and regulatory frameworks. The EU's progress in market harmonisation—through Flow-Based Market Coupling—enhances price signal fidelity, creating tactical windows for flexible industrial load. Yet beyond market mechanics, commercial tools such as indexed PPAs or hybrid contracts are needed to balance revenue certainty with optionality.

Equally important is recognising industrial flexibility as a grid service. Participation rules and incentives should treat responsive demand akin to energy storage—rewarding agility and transparency while safeguarding against local grid instability. As electricity systems become more complex, industrial loads like aluminium smelters must be seen not as passive consumers but as configurable grid assets.

7. Conclusions and Outlook

This study demonstrates that aluminium smelters can harness electricity market dynamics to improve profitability and grid stability – without compromising thermal integrity. By combining long-term PPAs with selective spot-market exposure, flexible procurement enables significant cost savings and turns volatility into opportunity.

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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