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 near-zero-emission solutions are achievable at modest cost premiums when renewables, electrification, and storage are optimally combined.

Integration of renewable energy and storage is central to decarbonizing aluminium smelters. Studies demonstrate that over 40 % of smelter power can be sourced from PV alone in high-solar regions, with demand response (flexible potline operation) reducing reliance on fossil backup and batteries [2]. Deeper decarbonisation—up to 100 % renewables—can be reached with larger PV, wind, battery, and hydrogen storage investments, at an estimated 26 % cost increase [2]. Regional analyses (e.g., Bizjak et al., 2024) [4] show that both large-scale on-site PV and strategic use of surplus solar can yield significant long-term savings. Moreover, smelters' inherent operational flexibility enables them to act as "virtual batteries", adjusting electricity use to match intermittent renewable supply and support grid stability [4].

While power decarbonisation remains the primary focus, Carbon Capture and Utilisation (CCU) is emerging as a key enabler for achieving near-zero emissions in aluminium production—especially for "hard-to-abate" process CO_2 from Hall–Héroult cells. Though still mostly at pilot stage, studies (Li et al. [5], Lassagne et al.[6]) indicate that integrating CCU with smelter waste heat recovery can enable capture of up to 85 % of process CO_2 at an added cost of 2–5 % per tonne of aluminium. Broader reviews (Rissman et al. [7]) recognise CCU, efficiency, electrification, and hydrogen as core pathways to full industrial decarbonisation.

4. Modelling Plan/Methodology

This paper proposes an optimisation framework with an objective function to determine an optimal electricity generation mix such that the total energy cost is minimised while meeting a pre-defined decarbonisation target and maintaining operational reliability. The model incorporates several conventional and renewable generational technologies, along with energy storage systems, and Carbon Capture and Utilisation (CCU).

While the optimisation tool works across different sub-models and performs several iterations to determine the optimal generation mix, for the purpose of explanation the paper divides the optimisation tool across three broad sub-parts:

Hourly Supply-Demand Balance Model: It estimates the capacity and generation mix of generation and storage technologies, ensuring the demand requirement for the smelter is met during all hours in a year, i.e., supply-demand optimisation at an hourly (8760 h/y) level.

Financial Model: It estimates the levelized cost of electricity based on the capacity and generation output from the hourly supply-demand model using the capital and operating unit costs assumptions provided by the user

Optimisation Tool: It performs several iterations on the hourly supply-demand balance model and the financial model to determine the capacity and generation mix to achieve global minima or least levelized cost of electricity with constraints satisfied.

4.1 Hourly Supply-Demand Balance Model

The optimisation is designed such that the end users could select technologies from various options and further configure operational parameters for each, to ensure flexibility on output based on project requirements. General overview of the technologies included is as follows.

4.1.1 Generation and Storage Technology Options in the Tool

Combined Cycle Gas Turbine (CCGT):
CCGT technology is widely used for both base load and peaking power generation due to its high thermal efficiency and operational flexibility. Inputs such as thermal efficiency, emissions factors, startup and shutdown costs and operational constraints, such as minimum operating capacity, are fully configurable by the user.

Solar Energy:
Solar power generation is influenced by diurnal and seasonal variations in irradiance levels. The model captures this variability through hourly irradiance profiles that a user can input. Rather than detailing specific PV system components, the framework provides a representative generation profile. Detailed modelling of solar system configurations is left for future work.

Wind Energy:
Wind power generation depends on fluctuating wind speeds across different locations and times. The model utilises an hourly wind speed profile to simulate these variations. Instead of detailed turbine-specific modelling, the framework captures a representative wind speed-to-power relationship and generation profile, sufficient for optimisation purposes

Nuclear Energy:
Nuclear power serves as a consistent baseload generation source. The framework captures the essential characteristics of nuclear generation, such as thermal efficiency and operational constraints, while simplifying reactor-specific details.

Hydropower:
The hydropower component is designed to reflect general operational characteristics of both reservoir-based and run-of-river systems. Configurable parameters include turbine-generator efficiency and capacity utilisation. Seasonal water availability and minimum flow constraints are represented through a simplified generation profile.

Hydrogen:
Power production using hydrogen has been incorporated into the framework via generalised electrolysis efficiency. The model provides a simplified approach to representing hydrogen as a flexible energy carrier and storage medium.

Battery Energy Storage System (BESS 4 h and 6 h):
BESS is modelled to simulate short-duration energy storage solutions with high round-trip efficiency. Key components that the model allows user to configure include battery capacity, charge/discharge efficiency, and degradation rates. This flexibility ensures realistic integration into various grid scenarios.

Long-Duration Energy Storage (LDES):
LDES systems extend storage capacity over longer periods, providing resilience against prolonged renewable generation shortfalls. The model includes configurable parameters such as energy storage capacity, charge/discharge rates, and round-trip efficiency. It supports multiple storage technologies, including pumped hydro and advanced thermal storage systems, enabling users to tailor the model to specific long-duration storage applications

Carbon Capture and Utilisation (CCU):
CCU technology is included to mitigate emissions from fossil-fuel-based power plants. Detailed configurations, such as post-combustion and pre-combustion capture systems tailored to specific plant requirements, are not modelled in depth.

The model assumes solar, wind, nuclear, hydropower, hydrogen to be emissions free power generation technologies therefore contribute towards meeting the decarbonisation target specified by the user.

4.1.2 Mathematical Equations

The electricity supplied each hour comes from two sources, the generation technologies (like gas, solar, wind, etc.) and the discharge from the energy storage systems adjusted for efficiency losses. For every time interval (hour), the total supply comprising direct generation and the usable portion of storage discharge must be at least as large as the sum of the system demand and the electricity being charged into storage. This ensures that all end-user demand is met, and any additional electricity stored for future use is also fully accounted for in the supply requirement. In simple, for every hour,

$$\text{Total Generation} + \text{Total Storage Discharge (adjusted for efficiency)} \geq \text{Demand} + \text{Total Storage Charge (adjusted for efficiency)}$$

4.1.3 Input Assumptions

Table 1. Operating assumptions for generation and storage technologies.

Component	CCGT	Solar	Wind	Nuclear	Hydro	Hydrogen	CCU	BESS	LDES
Thermal Efficiency (%)	51	100	100	33	100	65	100	85	85
Min. Capacity (%)	30	-	-	-	-	-	-	-	-

Table 2. Example of hourly generation profile (normalised).

Hour	CCGT	Solar	Wind	Nuclear	Hydro	BESS	LDES
00:00	0.75	0.00	0.30	1.00	0.95	0.00	0.50
06:00	0.70	0.10	0.40	1.00	0.95	0.10	0.60
12:00	0.60	0.90	0.35	1.00	0.95	0.30	0.70
18:00	0.65	0.40	0.50	1.00	0.95	0.50	0.80
23:00	0.80	0.00	0.25	1.00	0.95	0.20	0.40

4.2 Financial Model

4.2.1 Mathematical Equations

Capital Expenditures (CapEx)

CapEx represents the upfront costs of project development including equipment, installation, and supporting infrastructure. The total CapEx for a given technology is calculated as follows.

$$\text{Total CapEx (\$)} = \text{CapEx Input } (\$/kW) \times \text{Capacity (GW)} \times 10^6 \tag{1}$$

For estimation of Net cost of energy for each technology, CapEx is annualized using cost of capital and lifetime of each technology, as follows:

$$\text{Annualised CapEx (\$)} = Total\ CapEx \times \left(\frac{\text{WACC}}{\mathbf{1}-(\mathbf{1}+\text{WACC})^{-\text{Lifetime}}}\right) \tag{2}$$

Where:
$WACC$ Weighted Average Cost of Capital, %
Lifetime is expressed in years

Annual Operating Expenditure (OpEx)
The operating costs for each technology are divided into fixed and variable costs, where fixed costs are independent of the energy generation or capacity utilisation (e.g., routine maintenance, labor costs) while variable costs depend on the amount of generation (e.g., fuel cost, variable operation and maintenance (O&M)).

$$\text{Fixed OpEx (\$)} = \text{Fixed O\&M (\$/kW)} \times \text{Capacity (GW)} \times 10^6 \tag{3}$$

$$\text{Variable OpEx(\$)} = \text{Variable O\&M (\$)} + \text{Fuel Cost (\$)} \tag{4}$$

where

$$\text{Variable O\&M (\$)} = \text{Variable OpEx } (\$/MWh) \times \text{Annual Generation (GWh)} \times 10^3 \tag{5}$$

and

$$\text{Fuel Cost (\$)} = \text{Fuel Cost } (\$/MWh) \times \frac{\text{Annual Generation (GWh)}}{\text{Thermal Efficiency}} \times 10^3 \tag{6}$$

This calculation accounts for the unit price of the fuel (e.g., natural gas, hydrogen) and system efficiency, which dictates how much fuel is required to produce a given amount of energy. Fuel costs are a major determinant of the total operating cost for thermal and hydrogen-based systems.

4.2.2 Input Assumptions

The cost assumptions presented in Table 3 are highly preliminary and are based on the authors' understanding of the market. These assumptions are fully configurable, allowing users to tailor the model to specific market conditions, technological advancements, or policy environments. By adjusting inputs, users can explore the sensitivity of financial outcomes to key parameters, providing valuable insights for strategic decision-making.

Table 3. Input cost assumptions for generation and storage technologies.

Component	**Unit**	**CCGT**	**Solar**	**Wind**	**Nuclear**	**Hydro**	**Hydrogen**	**CCU**	**BESS 4 h**	**BESS 6 h**	**LDES**
CapEx	$/kW	1200	700	1200	5500	2000	1200	0	870	1220	1950
Fixed OpEx	$/kW·y	34	10	30	124	60	0	0	4	4	25
Other fixed Cost	M$/y	50	0	0	0	0	0	0	0	0	0
Variable OpEx	$/MWh	0.5	0	0	0	0	0	200	0	0	0
Fuel Cost	$/MWh	15	0	0	0	0	135	0	0	0	0

4.3 Optimisation Tool

The optimisation model is formulated to minimise the total cost of energy solution, subject to a range of operational and environmental constraints that a user can provide. The model incorporates decision variables such as installed capacity, energy generation, and storage utilisation.

The objective function in the optimisation tools is as follows:

$$\text{Minimize}\, Z = \sum_{j\in\text{Tech}}\left(OC_j\cdot C_j + FC_j\cdot C_j + \sum_{t\in\text{Time}} VC_j\cdot E_{j,t}\right) + \sum_{k\in\text{Storage}}(OC_k\cdot SC_k + FC_k\cdot SC_k) + \sum_{ccu\in\text{CCU}}\sum_{t\in\text{Time}} VC_{ccu}\cdot CCUS_{ccu,t} \tag{7}$$

where:

Z	Net cost of energy generation, $
OC_j	Operational cost for each generation technology j, $/GW
C_j	Installed capacity for each generation technology j, GW
FC_j	Annualized capital cost for each generation technology j, $/GW
VC_j	Variable cost for each generation technology j, $/MW
$E_{j,t}$	Energy generated by generation technology j at time t, MWh
OC_k	Operational cost for each storage technology j, $/GW
SC_k	Installed capacity for each storage technology k, MWh
FC_k	Fixed cost for each storage technology j, $/GW
VC_{ccu}	Variable cost for amount of CO_2 captured by CCU technology, $/t
$CCU_{ccu,t}$	Amount of CO_2 captured by CCU technology CCU at time t, t

The above objective function can be also described as:

$$\textit{Total Cost of Energy Solution (Z)} = \text{Cost of Energy Generation} + \text{Cost of Energy Storage} + \text{Cost of CCU} \tag{8}$$

Where:

$$\text{Cost of Energy Generation} = \textstyle\sum_{j\in\text{Tech}}\left(OC_j\cdot C_j + FC_j\cdot C_j + \sum_{t\in\text{Time}} VC_j\cdot E_{j,t}\right)$$

$$\text{Cost of Energy Storage} = \textstyle\sum_{k\in\text{Storage}}(OC_k\cdot SC_k + FC_k\cdot SC_k)$$

$$\text{Cost of CCU} = \textstyle\sum_{\text{ccu}\in\text{CCU}}\sum_{\text{t}\in\text{Time}} \text{VC}_{\text{ccu}}\cdot \text{CCU}_{\text{ccu,t}}$$

4.3.1 Constraints and Boundary Conditions

Hourly Demand Satisfaction

This constraint ensures that the total electricity generation and discharged energy from storage meets or exceeds the electricity demand at each time step (hour). To maintain energy balance, the function accounts for the energy charged into storage along with demand to exceed total generation. Mathematical equation of the modelled constraint is:

$$\textstyle\sum_{j\in\text{Tech}} E_{j,t} + \sum_{k\in\text{Storage}} \text{Dch}_{k,t}\cdot\eta_k^{\text{discharge}} \geq D_t + \sum_{k\in\text{Storage}} \text{Ch}_{k,t} \qquad \forall t \tag{9}$$

where:

$E_{j,t}$	Electricity generated by technology j at time t
$Dch_{k,t}$	Electricity discharged from storage k at time t
$\eta_k^{discharge}$	Discharge efficiency of storage k, %
D_t	Electricity Demand at time t

$Ch_{k,t}$	Electricity charged into storage k at time t

Decarbonisation Target Fulfillment

The decarbonisation percentage target defined by the user is interpreted as equivalent percentage of emissions reduction versus a 0 % decarbonized scenario. This constraint limits the 'non-carbon captured' electricity generation from CCGT to be equal to the acceptable level of non-decarbonized electricity, as defined by the user.

$$\sum_t E_{\mathrm{CCGT},t} - \sum_{ccu \in \mathrm{CCU}} CCU_{ccu,t} = \left(1 - r_{\mathrm{green}}\right) \times \sum_t D_t \tag{10}$$

where:

$E_{CCGT,t}$	Energy generated by CCGT at time t
$CCU_{ccu,t}$	Carbon capture from CCU technology at time t
r_{green}	Decarbonisation target defined by the user
D_t	Demand at time t

Storage Operation and State of Charge (SoC)

This constraint models the state of charge (SoC) of energy storage systems. It ensures that the energy stored in each storage unit is updated dynamically, considering the efficiencies of charging and discharging processes.

$$\mathrm{t} = 1: \quad SoC_{k,t} = \mathrm{Ch}_{k,t} \cdot \eta_k^{\mathrm{charge}} - \mathrm{Dch}_{k,t} \cdot \eta_k^{\mathrm{discharge}^{-1}}$$

$$\mathrm{t} > 1: \quad SoC_{k,t} = \mathrm{SoC}_{k,t-1} + \mathrm{Ch}_{k,t} \cdot \eta_k^{\mathrm{charge}} - \mathrm{Dch}_{k,t} \cdot \eta_k^{\mathrm{discharge}^{-1}} \tag{11}$$

$$\forall k \in \text{Storage}, \ \forall t$$

where:

$SoC_{k,t}$	State of charge of storage k at time t
$Ch_{k,t}$	Energy charged into storage k at time t
$Dch_{k,t}$	Energy discharged from storage k at time t
η_k^{charge}	Charging efficiency of storage k
$\eta_k^{discharge}$	Discharge efficiency of storage k

Minimum and Maximum CCGT Utilisation

This constraint ensures that the CCGT technology operates above a minimum utilisation threshold, thus maintaining operational reliability and efficiency.

$$E_{\mathrm{CCGT},t} \geq \mathrm{min\_util} \times GR_{t,\mathrm{CCGT}} \times C_{\mathrm{CCGT}} \quad \forall t \tag{12}$$

where:

$E_{CCGT,t}$	Energy generated by CCGT at time t
min_util	Minimum utilisation percentage, %
$GR_{t,CCGT}$	Generation ratio of CCGT at time t
C_{CCGT}	Capacity of CCGT

Charging Constraints for Green Energy

This constraint ensures that energy charged into storage is limited to the energy generated by green technologies, ensuring that discharges later contribute to green energy compliance.

$$\sum_{k \in \text{Storage}} \text{Ch}_{k,t} \leq \sum_{j \in \text{GreenTech}} E_{j,t} \quad \forall t \tag{13}$$

where:

$Ch_{k,t}$	Energy charged into storage k at time t
$E_{j,t}$	Energy generated by green technology j at time t

Excess Generation Constraint

Based on the cap defined by user on permissible total excess generation by all technologies, this constraint prevents overproduction of energy beyond a certain ratio of the total demand across all time periods, ensuring cost-effectiveness and system stability.

$$\sum_{t \in \text{Time}} \left(\sum_{j \in \text{Tech}} E_{j,t} - \sum_{k \in \text{Storage}} \text{Ch}_{k,t} \cdot \eta_k^{\text{charge}} + \text{Dch}_{k,t} \cdot \eta_k^{\text{discharge}-1} - D_t \right) \leq \text{max\_excess\_ratio} \times \sum_{t \in \text{Time}} D_t \tag{14}$$

where:

$E_{j,t}$	Energy generated by technology j at time t
$Ch_{k,t}$	Energy charged into storage k at time t
η_k^{charge}	Charging efficiency of storage k
$Dch_{k,t}$	Energy discharged from storage k at time t
$\eta_k^{discharge}$	Discharge efficiency of storage k
D_t	Demand at time t
max_excess_ratio	Maximum allowed excess generation ratio defined by user

Storage Capacity Limits

This constraint ensures that the charging, discharging, and state of charge do not exceed the storage capacity limits, preserving operational integrity.

$$\text{Ch}_{k,t} \leq SC_k \quad \text{Dch}_{k,t} \leq SC_k \quad \text{SoC}_{k,t} \leq SC_k \times \text{duration}_k \quad \forall k, t \tag{15}$$

where:

$Ch_{k,t}$	Energy charged into storage k at time t
$Dch_{k,t}$	Energy discharged from storage k at time t
$SoC_{k,t}$	State of charge of storage k at time t
SC_k	Capacity of storage k
$duration_k$	Duration factor of storage k

5. Scenario Analysis

To evaluate the impact of varying decarbonisation targets on energy generation, storage utilization, cost, and emissions, a series of scenario runs were conducted using the optimization framework. Each scenario represents a specific decarbonisation target (ranging from 0 % to 80 %) for which the optimization tool returned different configurations of generation technologies, storage systems, and carbon capture, such that the net electricity cost is minimum. The analysis aims to identify cost-optimal solutions while ensuring reliable energy supply and minimizing CO_2 emissions. This section details the result of the scenario runs and shares key insights from the results.

5.1 Scenario Runs

Table 4 (below) presents the results of five scenarios runs corresponding to different decarbonisation targets (0 %, 20 %, 40 %, 60 %, and 80 %) defined by the user. Key metrics include the net levelized cost of electricity (LCOE), total CO_2 emissions, generation capacity mix, excess generation percentage, and storage utilisation. All generation (except hydro) and storage technologies were enabled for all the five scenarios based on the cost and operating assumptions outlined in tables 1, 2 and 3 above.

Table 4. Scenario runs – decarbonisation tool.

Scenario Name	**Sc. 1**	**Sc. 2**	**Sc. 3**	**Sc. 4**	**Sc. 5**
INPUT					
Hourly Peak Demand (MW)	1 000				
Demand Profile	Baseload				
Excess Generation Allowed (%)	30				
Decarbonisation target (%)	0	20	40	60	80
OUTPUT					
LCOE (USD/MWh)	34	40	46	62	86
Decarb Achieved (%)	0	20	40	60	80
Unmet Demand (MW)	0	0	0	0	0
Excess Energy Generated (%)	0	5	9	8	7
Optimised Capacity Mix >>					
CCGT (MW)	1 000	1 000	1 000	736	368
Solar (MW)	0	589	754	603	302
Wind (MW)	0	0	570	611	305
Nuclear (MW)	0	0	0	264	632
Hydrogen (MW)	0	0	0	0	0
Hydro (MW)	0	0	0	0	0
Storage 4h (MW)	0	0	0	0	0
Storage 6h (MW)	0	0	0	0	0
Storage LDES12h (MW)	0	0	0	0	0
Generation Mix >>					
CCGT (GWh)	8 760	7 008	5 256	3 504	1 752
Solar (GWh)	0	1 752	2 244	1 795	898
Wind (GWh)	0	0	1 724	1 849	925
Nuclear (GWh)	0	0	0	2 315	5 537

Hydrogen (GWh)	0	0	0	0	0
Hydro (GWh)	0	0	0	0	0
CCU Capture Output (t CO2)	0	0	0	0	0
Total CO2 Emission (t)	3 504 000	2 893 200	2 102 400	1 401 600	700 800

5.2 Insights and Comparisons

5.2.1 LCOE Increases with Higher Decarbonisation Targets

As the decarbonisation target increases from 0 to 80 %, the levelized cost of electricity (LCOE) increases from 34 USD/MWh to 86 USD/MWh. This increase is driven by the higher costs of integrating renewable energy, storage technologies, and CCU systems. At 60 % decarbonization, LCOE reaches 62 USD/MWh, reflecting the growing dependence on expensive low-carbon baseload generation technologies such as nuclear to replace CCGT.

5.2.2 CO_2 Emissions Reduction

Total CO_2 emissions decrease proportionately with higher decarbonization targets. 0 % decarbonization emits 3 504 000 tonnes of CO_2 while 80 % decarbonization leads to 700 800 tonnes of CO_2 emission. This demonstrates the effectiveness of the optimization framework in reducing emissions through the adoption of renewable and low-carbon energy generation technologies.

5.2.3 CCGT Capacity Declines

The capacity of Combined Cycle Gas Turbines (CCGT) decreases as decarbonisation targets increase – while 0 % decarbonisation requires 1000 MW CCGT base load to meet peak demand, 80 % Decarbonisation reduces the base load from CCGT to 368 MW. This indicates a shift towards renewable and low-carbon generation sources, with CCGT playing a reduced role in higher-decarbonisation scenarios. In future, if CCU proves to be cost competitive versus other generation technologies, CCGT capacity may not reduce and instead the emissions could be reduced through use of CCU.

5.2.4 Storage Utilisation

Battery Energy Storage Systems (BESS) and Long-Duration Energy Storage (LDES) was not required in these scenarios, but their potential role in future higher-demand cases is acknowledged with change in cost assumptions.

5.2.5 Balancing Excess Generation

Higher decarbonization targets lead to a slight increase in excess generation, peaking at 8 % in the 60 % scenario. This underscores the need for optimizing demand-side management, storage, and grid flexibility to harness surplus renewable energy effectively.

6. Conclusions and Future Directions

6.1 Conclusions

This study proposed a comprehensive optimization framework to design cost-effective and sustainable energy systems for aluminum manufacturing, a high energy-intensive industry. By 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.

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