Journal of Climate Change
ISSN 2395-7611 Volume 12 (2026) No. 2. pp. 238–249

https://doi.org/10.70917/jcc-2026-014
Article

Techno-economic assessment of low-cost adsorbents for CO_2 capture and mineralization in the UK aluminium industry

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Abstract: Decarbonising heavy industry demands cost-effective, scalable carbon capture pathways that go beyond simple storage. This study investigates the technical and economic viability of capturing CO_2 emissions from an aluminium smelter and converting them into stable magnesium carbonate materials through ex-situ mineral carbonation. Two distinct process routes are compared: one based on serpentinite rock (ultramafic feedstock) from the Ballantrae region of Scotland, which co-produces magnesium carbonate, nesquehonite, and silica sand; and one based on seawater brine, which yields only nesquehonite. Following a systematic evaluation of adsorbent materials, the serpentinite route was selected as the primary case for full techno-economic modelling. Applied to the ALVANCE British Aluminium smelter at Lochaber—which emits approximately 187,200 tonnes of CO_2 per year—a bottom-up capital expenditure (CAPEX) estimate of £152 million was developed, with annual operating expenditures (OPEX) of approximately £62.4 million. Revenue projections incorporating UK Emissions Trading System (ETS) carbon credits at £75 per tonne, magnesium carbonate sales at £260 per tonne, and silica by-product revenue yield a simple payback period of approximately 11 years and an after-tax internal rate of return (IRR) of 16%. The seawater route does not achieve financial break-even within a 20-year project horizon under the same assumptions. The findings demonstrate that on-site mineral carbonation at industrial cluster facilities can offer commercially viable CO_2 abatement while simultaneously producing construction materials with a negative carbon footprint.

Keywords: mineral carbonation; CO_2 capture; magnesium carbonate; serpentinite; techno-economic analysis; aluminium smelter; CCUS

1. Introduction

The urgency of addressing anthropogenic climate change has placed industrial decarbonisation at the forefront of global policy and research agendas. The Intergovernmental Panel on Climate Change (IPCC) has consistently underscored that limiting global warming to 1.5°C above pre-industrial levels requires not only the rapid phase-out of fossil fuels in the energy sector, but also deep emissions reductions across hard-to-abate industrial processes. Without concerted intervention in heavy industry, achieving net-zero targets by mid-century will remain out of reach. Industrial CO_2 emissions represent one of the most persistent and technically challenging dimensions of this global decarbonisation challenge. Unlike power-sector emissions—which can be substantially reduced through fuel switching and renewable energy deployment—process-related CO_2 from heavy industries such as aluminium smelting, cement production, and steel manufacturing is largely inescapable under current technology paradigms. The United Kingdom, ranked as Europe's second-largest CO_2 emitter, has committed to reducing 40 million tonnes of CO_2 by 2030, with carbon capture, utilisation, and storage (CCUS) expected to contribute significantly to meeting this goal (Leonzio, et al. 2020).

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Among available carbon management strategies, mineral carbonation has attracted growing attention because it permanently sequesters CO_2 in a thermodynamically stable solid form, eliminating the long-term monitoring requirements associated with geological storage. The process mimics the natural formation of limestone: CO_2 reacts with divalent metal cations—principally calcium and magnesium sourced from silicate minerals—to precipitate stable carbonates (Alper and Yuksel Orhan 2017) . Depending on feedstock and processing conditions, these products may include magnesium carbonate ($MgCO_3$), calcite ($CaCO_3$), or hydrated variants such as nesquehonite ($MgCO_3 \cdot 3H_2O$). Critically, several of these products have established or emerging commercial applications in construction, contributing additional revenue that can offset process costs.

Research indicates that mineralisation of industrial process residues could contribute up to 24 million tonnes, approximately 60% of the UK's CCUS-led CO_2 reduction target by 2030 (Hills, Tripathi and Carey 2021) . For mineral carbonation to transition from laboratory demonstration to industrial deployment, however, it must overcome two fundamental challenges: the kinetic sluggishness of carbonation reactions and the high energy and chemical inputs required for feedstock pre-treatment. The proximity of suitable mineral feedstocks to CO_2 point sources is equally critical, since transporting either CO_2 or minerals adds substantially to overall project costs.

This paper addresses these challenges by investigating the feasibility of deploying an on-site mineral carbonation plant at the ALVANCE British Aluminium smelter in Lochaber, Scotland—the last remaining primary aluminium smelter in the United Kingdom. Two process pathways are evaluated and compared: (1) carbonation using serpentinite feedstock from western Scotland, and (2) carbonation using seawater brine. The study develops bottom-up CAPEX and OPEX estimates, constructs a 20-year cash flow model incorporating carbon credit revenues and by-product sales, and draws conclusions regarding the economic viability and scalability of each approach.

2. Literature Review

2.1. Industrial Emissions and the Case for CCUS

The cement, iron and steel, and chemical sectors collectively account for the majority of global non-combustion process CO_2. These emissions arise from chemical transformations intrinsic to production—such as the calcination of limestone in cement kilns or the electrochemical reduction of alumina in aluminium smelting. The aluminium sector in particular presents opportunities for circular economy approaches; studies on recycled metal utilisation in casting alloys have demonstrated that energy consumption and carbon emissions can be substantially reduced through secondary feedstock integration (Gürkan 2025). Table 1 illustrates the approximate scale of these non-combustion emissions by sector (Hannah Ritchie 2020).

Table 1. Approximate non-combustion process CO_2 emissions by heavy industrial sector. Data adapted from (Hannah Ritchie 2020).

Industrial Sector	Annual CO_2 (Gt)	Approx. % of Global Total
Cement	2.2	~6%
Iron & Steel	2.8	~8%
Chemicals & Other	1.1	~3%

Despite incremental efficiency improvements, reducing these emissions to near-zero levels requires either fundamental process redesign or the deployment of carbon capture technologies. CCUS has therefore emerged as a critical bridging strategy, providing near-term emissions reductions while low-carbon process alternatives are developed and scaled (Gürkan 2025)(Riffat, J. and Samaei 2025).

2.2. Carbon Capture Technologies

Post-combustion capture technologies—including solvent absorption, solid adsorption, and membrane separation—are the most mature approaches for retrofitting existing industrial plants. A comparative performance analysis of indoor CO_2 capture methods across operational contexts has

further demonstrated the relevance of capture system selection to building and industrial emissions reduction (Shen and Yang 2026). Published estimates for CO_2 capture costs range from approximately €20 to €140 per tonne, depending on process configuration, scale, and local energy prices (Schneider, et al. 2011). Selecting the lowest-cost technology is rarely straightforward: cost comparisons across studies are often inconsistent due to differing assumptions, and many estimates derive from pilot-scale or modelling studies rather than full industrial deployments, introducing considerable uncertainty.

Carbon mineralisation distinguishes itself from conventional CCUS by simultaneously capturing and permanently storing CO_2 in solid carbonate form. This eliminates the need for geological injection infrastructure and long-term monitoring. The thermodynamics of mineral carbonation are inherently favourable: the reaction of CO_2 with metal oxides is exothermic, releasing heat that can be utilised within the process (Liu, et al. 2020).

2.3. Mineral Carbonation: Feedstocks and Chemistry

The primary challenge in mineral carbonation is sourcing reactive divalent metal cations (Ca^{2+} and Mg^{2+}) at adequate scale and cost. In nature, these cations are typically bound within silicate minerals, with the most promising feedstocks being serpentine ($Mg_3Si_2O_5(OH)_4$), olivine (Mg_2SiO_4), and wollastonite ($CaSiO_3$). The principal carbonation reactions are (Yoo, et al. 2022):

$$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O \quad (1)$$

$$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2 \quad (2)$$

$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2 \quad (3)$$

From a stoichiometric standpoint, olivine can sequester 0.62 tonnes of CO_2 per tonne of reactant, while serpentine and related ultramafic materials achieve approximately 0.4–0.5 tonnes CO_2 per tonne (Kelemen, et al. 2020). Overall, between 1.6 and 3.7 tonnes of rock are typically required to permanently sequester one tonne of CO_2, depending on mineral composition and conversion efficiency (Alper and Yuksel Orhan 2017).

2.4. Ex-Situ versus In-Situ Mineral Carbonation

Mineral carbonation may be implemented either ex-situ—where minerals are quarried and reacted in surface reactors—or in-situ, where CO_2 is injected underground to react with subsurface minerals. In-situ carbonation avoids additional surface infrastructure and uses geothermal heat to drive reactions, but requires host rocks with high permeability and readily soluble metal cations (Matter, et al. 2014). Ex-situ carbonation, the focus of this study, offers greater process control and the ability to produce marketable solid products.

Ex-situ carbonation may proceed via direct or indirect routes. Direct aqueous carbonation occurs in a single solution where CO_2 dissolution, metal ion leaching, and carbonate precipitation happen simultaneously; reaction rates can be accelerated by elevated temperature and pressure or increased CO_2 concentration (Gerdemann, et al. 2003). Indirect carbonation separates metal extraction from carbonation into distinct steps, allowing independent optimisation. The governing reactions for the indirect route are (Yoo, et al. 2022):

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^- \quad (4)$$

$$Ca/Mg\ (silicate) + 2H^+ \rightarrow Ca^{2+}/Mg^{2+} + SiO_2 + H_2O \quad (5)$$

$$Ca^{2+}/Mg^{2+} + HCO_3^- \rightarrow CaCO_3/MgCO_3 + H^+ \quad (6)$$

2.5. Magnesium Carbonate from Serpentinite

Serpentinite dissolution studies have demonstrated that leaching in 4M HCl or HNO_3 at 70°C extracts over 88% of the magnesium content into solution, leaving most silica undissolved. Bubbling CO_2 through the purified magnesium-rich solution while raising pH with NaOH causes rapid precipitation of hydromagnesite ($Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$). The optimal precipitation pH is approximately 9, at which up to 94% of dissolved magnesium precipitates as 99% pure hydromagnesite with a carbonate content of around 50% (Teir, et al. 2007). Chemical costs—estimated at $600–1,600 per tonne CO_2 stored when acids and NaOH are not recycled—remain the primary barrier to commercial viability without high-value by-product revenue.

2.6. Nesquehonite Production via Seawater

An alternative route uses desalination brine or seawater, which naturally contains dissolved Mg^{2+} and Ca^{2+}, to precipitate nesquehonite ($MgCO_3 \cdot 3H_2O$) through reaction with CO_2-laden flue gas. The four-stage process described by Gálvez-Martos et al. (Galvez-Martos, et al. 2020) involves: (1) CO_2 absorption into brine with simultaneous $CaCO_3$ precipitation; (2) NaOH addition to raise pH and precipitate nesquehonite; (3) mild drying; and (4) thermal dehydration at approximately 100°C over 24 hours to produce reactive anhydrous magnesium carbonate.

The resulting material contains approximately 30% permanently mineralised CO_2 and exhibits cementitious binding properties on rehydration, analogous to conventional plasterboard production (Galvez-Martos, et al. 2021). The high NaOH consumption—approximately 1.8 mol alkali per mol CO_2 absorbed under optimised conditions—is the principal economic challenge for this route.

2.7. Amine Looping

Aqueous amine-bearing solvents, such as monoethanolamine (MEA), can enhance CO_2 hydration and carbonate precipitation under mild conditions. The amine looping pathway cycles solvents between CO_2-loaded and CO_2-released states by converting CO_2 into mineral carbonates (Liu, et al. 2020) . Despite its conceptual appeal, this approach has not been demonstrated at industrial scale, and current MEA market costs make it economically uncompetitive as a mineralisation pathway. It is therefore excluded from the quantitative analysis in this study.

3. Methodology

The research approach is structured in four stages. First, a systematic literature review was conducted to identify and compare low-cost adsorbent and feedstock materials for mineral carbonation, evaluating candidates on cost, availability, reaction rates, and CO_2 uptake capacity. This review informed the selection of two primary process pathways for detailed analysis: the serpentinite route and the seawater brine route.

Second, the ALVANCE British Aluminium smelter at Lochaber, Scotland was selected as the industrial case study. This facility provides a well-defined point source of CO_2 emissions (approximately 187,200 tonnes per year at 3.9 tCO_2/t Al) and its location near both the Ballantrae serpentinite deposits and Loch Linnhe makes both feedstock options practically accessible without long-distance transport.

Third, a bottom-up CAPEX estimate was developed for each process route by costing major equipment items individually—including mineral pre-processing mills, CO_2 absorption columns, causticization tanks, carbonation reactors, and secondary mineral processing equipment—drawing on literature benchmarks for comparable mineral carbonation systems (Hitch and Dipple 2012) (Anantharaman, et al. 2018) . Installation factors, ancillary materials, engineering costs, and a 25% contingency allowance were applied. Annual OPEX was estimated by summing labour, maintenance (3% of CAPEX), energy consumption (1.1 GJ per tonne CO_2 at £86/GJ), raw material costs, and chemical costs (NaOH and HNO_3 at £150/tonne) (Sanna, Steel and Maroto-Valer 2017).

Fourth, a 20-year discounted cash flow model was constructed assuming: CAPEX financed at 5% interest over the project life; a Capital Recovery Factor (CRF) derived accordingly; 5% annual inflation applied to revenues and costs; 20% tax on profits; and a 10% discount rate for net present value (NPV) calculations. Revenue streams comprised ETS carbon credits at £75/tonne CO_2 (applied to 73% of captured CO_2, accounting for process emissions of approximately 27% (Metz, et al. 2005)), magnesium carbonate and nesquehonite sales at £260/tonne, and silica sand sales at £85/tonne (serpentinite route only). Simple payback period and after-tax IRR were the primary viability metrics.

The serpentinite feedstock was assumed to originate from the Ballantrae ophiolite belt in western Scotland. Two serpentinite belts exist in this region—a northern belt of approximately 12 km^2 and a southern belt of approximately 20 km^2. Assuming open-pit quarrying to 30 m depth and a rock density of 2.6 tonnes/m^3, the theoretical resource exceeds 2,500 million tonnes, with a stoichiometric CO_2 storage potential of approximately 900 million tonnes (Styles, et al. 2014).

The Ballantrae serpentinite is composed of 92.3% lizardite and 7.5% chrysotile, making it well-suited for carbonation applications. The overall carbonation process, from raw material input to product verification, is illustrated in Figure 1.

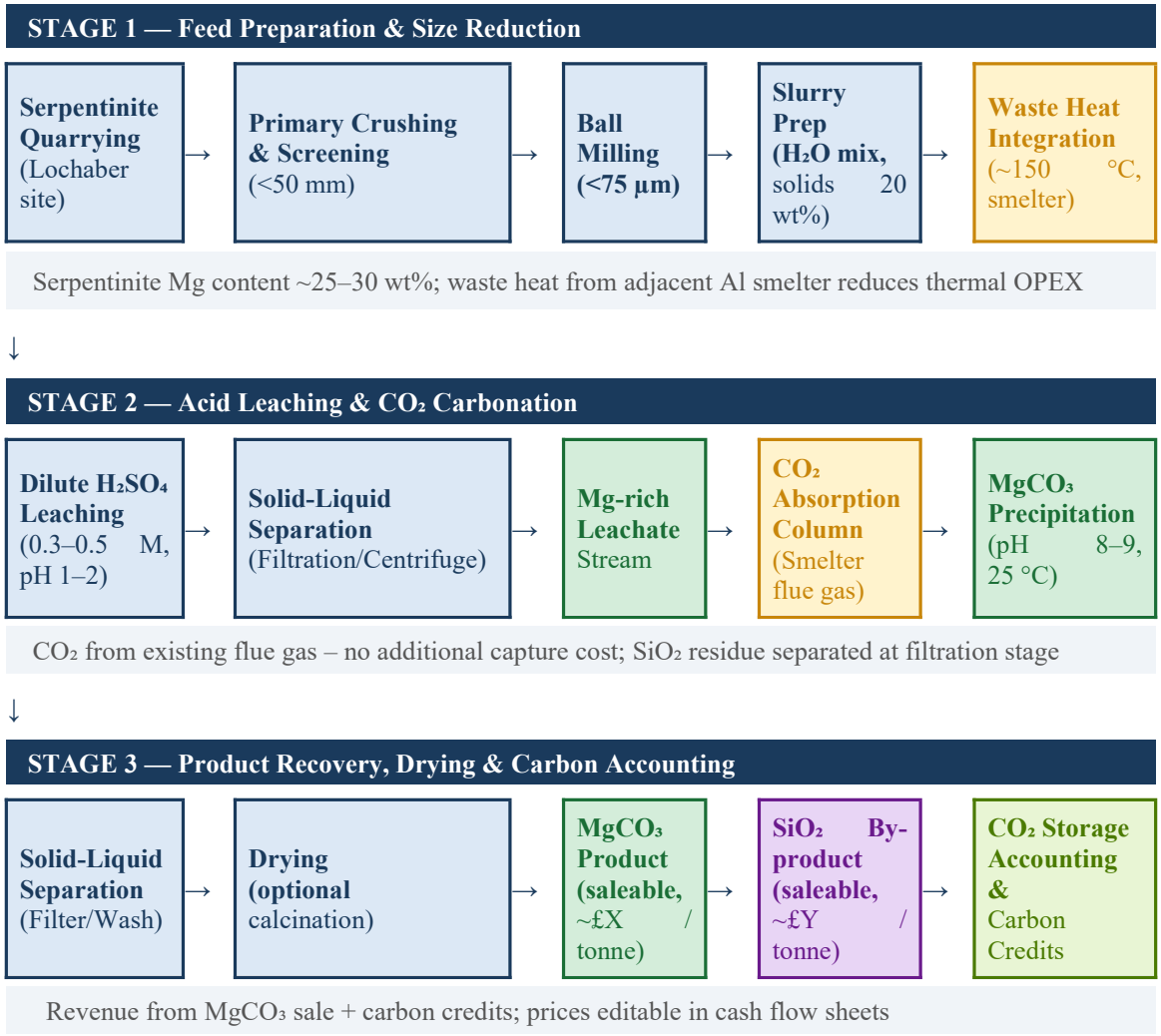

Figure 1. Simplified process flow diagram of the serpentinite mineral carbonation route at the Lochaber smelter. Box colours indicate processing unit operations (blue), chemical and energy inputs (yellow), separation steps (purple), and accounting and verification steps (green).

4. Case Study: ALVANCE British Aluminium Smelter, Lochaber

4.1. Company Background and CO_2 Profile

ALVANCE British Aluminium, a member of the GFG Alliance, operates the Lochaber smelter in the Scottish Highlands—the sole surviving primary aluminium smelter in the United Kingdom. Founded in 1929, the facility generates up to 48,000 tonnes of aluminium per year. Powered substantially by hydroelectric generation from the Ben Nevis catchment, it reports a carbon intensity of approximately 3.9 tCO_2/t Al, giving rise to annual process emissions of approximately 187,200 tonnes CO_2. Its geographic proximity to Loch Linnhe and to the Ballantrae serpentinite deposits makes it a strategically advantaged location for on-site mineral carbonation.

4.2. Aluminium Smelting Process and CO_2 Generation

Industrial aluminium production relies on the Hall–Héroult electrolytic process, in which dissolved alumina (Al_2O_3) is reduced using carbon anodes in a molten cryolite electrolyte. The fundamental electrochemical reaction is:

$$\tfrac{1}{2}Al_2O_3\,(dissolved) + \tfrac{3}{4}C(s) \rightarrow Al(l) + \tfrac{3}{4}CO_2(g) \quad (7)$$

In practice, carbon anode consumption exceeds stoichiometric predictions: approximately 0.4–0.45 kg carbon is consumed per kilogram of aluminium produced (versus the theoretical 0.33 kg), yielding around 1.5 kg CO_2 per kg aluminium. This excess arises from process impurities and from the anode

effect—a transient condition in which an insulating gas layer forms beneath the anode, increasing cell voltage and altering anode gas composition from primarily CO_2 to a mixture including perfluorocarbons (CF_4) with very high global warming potential. Minimising the frequency and duration of anode effects is therefore a key emissions management priority.

Exhaust gases from the electrolysis cells are captured by superstructure hoods and treated via dry scrubbing, in which alumina powder adsorbs hydrogen fluoride (HF) and sodium tetrafluoroaluminate particulates before the cleaned gas is vented to atmosphere. This treated flue gas constitutes the feed stream for the proposed mineral carbonation system (Kvande and Drablos 2014).

5. Techno-Economic Analysis

5.1. Capital Expenditure (CAPEX)

A bottom-up CAPEX estimate was developed for the serpentinite-based mineral carbonation plant, sized to process the full 187,200 tCO_2/year from the Lochaber smelter, assuming a conversion ratio of 0.5 tonnes CO_2 per tonne of serpentine (Hitch and Dipple 2012). Table 2 summarises the capital cost breakdown.

Table 2. Estimated capital expenditure breakdown for the serpentinite mineral carbonation plant (187,200 tCO_2/yr capacity). Data adapted from (Hitch and Dipple 2012).

Capital Cost Item	Estimated Cost
Mineral pre-processing equipment (crushers, mills)	£12.1 million
CO_2 absorption columns	£19.4 million
Causticization tanks	£6.2 million
Carbonation reactors	£17.0 million
Secondary mineral processing	£9.3 million
Construction and installation	£22.0 million
Piping	£8.1 million
Electrical, instrumentation and controls	£15.2 million
Engineering and contingency (~25%)	£42.0 million
Total CAPEX	£152 million

The equivalent CAPEX for the seawater-based route was estimated at £140 million, reflecting the reduced pre-processing requirements of a liquid feedstock. Annualised CAPEX (ACAPEX) was calculated using the Capital Recovery Factor (CRF):

$$CRF = [i \times (1 + i)^n] / [(1 + i)^n - 1] \quad (8)$$

With an interest rate (i) of 5% and plant life (n) of 20 years, CRF = 0.08, giving ACAPEX values of £12.16 million/year (serpentinite) and £11.2 million/year (seawater).

5.2. Operating Expenditure (OPEX)

Annual OPEX for the serpentinite route was estimated by aggregating the individual cost components in Table 3. NaOH and HNO_3 consumption is the dominant cost: the mineralisation process requires approximately 1.1 kg NaOH per kilogram of CO_2 removed, reflecting a molar ratio of 1.2:1 (Sanna, Steel and Maroto-Valer 2017) . At a European contract price of £150/tonne, this constitutes nearly half of total OPEX. Energy consumption at 1.1 GJ/tCO_2 is the second largest cost driver.

Table 3. Annual operating expenditure breakdown for the serpentinite mineral carbonation process.

Operating Expense	Cost per Unit	Annual Cost (£)
Maintenance	3% of CAPEX	4,560,000
Labour	30% of maintenance	1,368,000
Energy consumption	£86/GJ	17,709,120
Raw material (serpentine)	£7/tonne	2,620,800
NaOH and HNO_3	£150/tonne	30,888,000
Mineral pre-processing	£14/tonne	5,241,600
Total OPEX	—	£62,387,520

For the seawater route, raw material and mineral pre-processing costs are eliminated, reducing total OPEX to approximately £54.5 million per year. However, the seawater route generates no silica sand by-product, significantly reducing revenue.

5.3. Revenue Projections

Two primary revenue streams are incorporated into the financial model. Carbon credits are valued at £75/tCO_2, consistent with UK ETS permit price forecasts of €65–103/tonne for 2023 (ICE Benchmark Administration 2024) . Because ex-situ mineralisation itself generates CO_2 equivalent to approximately 27% of captured emissions (Metz, et al. 2005), credits are calculated on 73% of gross captured CO_2:

$$\textit{Carbon credit revenue} = 0.73 \times 187{,}200\ t/yr \times £75/t = £10{,}249{,}200/yr \quad (9)$$

For the serpentinite route, silica sand produced as a co-product (approximately 0.67 tonnes SiO_2 per tonne CO_2 mineralised) is sold at £85/tonne:

$$\textit{Silica revenue} = 0.67 \times 187{,}200\ t/yr \times £85/t = £10{,}661{,}040/yr \quad (10)$$

Combined with magnesium carbonate and nesquehonite sales at £260/tonne, total first-year revenue for the serpentinite route is approximately £69.6 million. For the seawater route, the absence of silica by-product and the lower NQ selling price (£60/tonne) reduce first-year revenue to approximately £21.5 million.

5.4. Cash Flow Analysis

Figure 2 presents the cash flow results for the first 20 years of the serpentinite and seawater projects, incorporating 5% annual inflation, 20% tax on profits, and a 10% discount rate. All values are in millions of pounds.

Cumulative net savings turn positive between Year 11 and Year 12, confirming a simple payback period of approximately 11 years. Over the full 20-year project life, the serpentinite project generates approximately 9 years of cumulative positive net cash flows. The after-tax IRR, calculated over the 20-year operational period, is estimated at 16%—substantially exceeding the assumed 5% cost of capital and broadly competitive with returns expected from infrastructure investments.

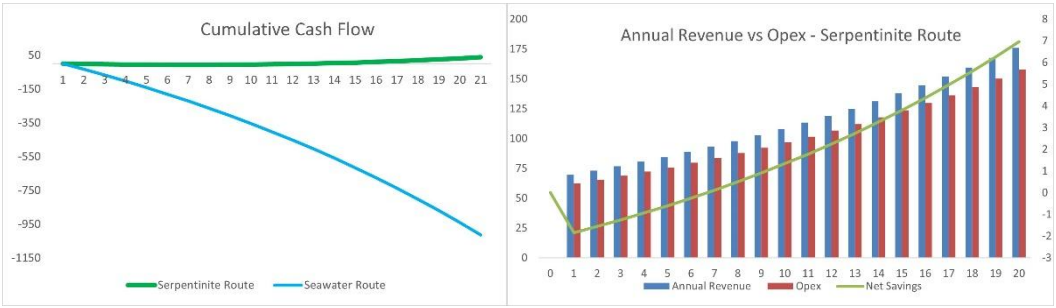

Figure 2. Cumulative cash flow (left) and annual revenue vs. OPEX (right) for the serpentinite and seawater routes over the 20-year project life.

The seawater route generates consistently negative net savings throughout the 20-year project horizon, with cumulative losses deepening from approximately –£33.4 million in Year 1 to approximately –£400 million by Year 10. The lower revenue from NQ alone (£60/tonne), combined with the absence of silica by-product revenue, is structurally insufficient to cover OPEX plus CAPEX recovery. Significant reductions in alkali costs, improvements in chemical recovery, or uplifts in NQ market pricing would be required before the seawater route could achieve viability.

6. Discussion

The results presented here carry several important implications for the broader deployment of mineral carbonation as an industrial CCUS technology.

First, the economic case for on-site deployment in industrial clusters is compelling. Rail transport of captured CO_2 adds approximately £5/tCO_2 per 500 km, increasing total costs by more than 50% for the annual volumes considered here (Fasihi, Efimova and Breyer 2019). By situating the carbonation plant directly adjacent to the aluminium smelter, all transport costs are eliminated; CO_2-bearing flue gas can

be piped directly from the smelter exhaust treatment system to the carbonation reactor. The availability of serpentinite feedstock within a short logistics chain from the Ballantrae belt reinforces the geographic advantage.

Second, the industrial symbiosis model—where carbonation co-products are sold to or utilised by neighbouring industries—is a critical lever for optimising project economics. The estimated net carbon capture cost of approximately £90/tCO_2 (£301.6 million total expenditures against £391.95 million total revenues over the project life) sits within the upper end of the published cost range of €20–140/t CO_2 (Schneider, et al. 2011) but is economically defensible given the multiple value streams involved.

Third, the contrast between the serpentinite and seawater routes highlights the critical role of by-product economics. The serpentinite route's profitability stems from the combined revenue of magnesium carbonate, nesquehonite, and silica sand; carbon credits alone would be insufficient to offset OPEX. The seawater route's structural financial imbalance—driven by high NaOH consumption and the absence of silica co-product—cannot be resolved within the current model framework.

Fourth, important uncertainties are embedded in the analysis. CAPEX estimates are based on literature benchmarks rather than supplier quotations, introducing potential variations of ±30–50% until detailed engineering design is completed. NaOH prices are sensitive to electricity prices, and the trajectory of UK ETS carbon credit pricing remains subject to regulatory change. Sensitivity analyses (not reported in detail here) suggest that the serpentinite project maintains positive cumulative cash flows under modest adverse deviations in individual parameters, indicating reasonably robust underlying economics.

Fifth, it is worth comparing the serpentinite carbonation route against alternative decarbonisation pathways available to aluminium smelters to contextualise the findings. Electrification of process heat, while increasingly viable in the energy sector, does not address process CO_2 from anode oxidation—the dominant emission source in Hall–Héroult smelting. Inert anode technology, which would produce oxygen instead of CO_2 at the anode, represents the most radical process transformation and would eliminate the fundamental emission source entirely (Kvande and Drablos 2014); however, inert anodes remain at pre-commercial stage and face significant materials science challenges. Carbon capture with geological storage (CCS) is technically feasible but requires CO_2 compression, transport, and injection infrastructure, adding costs estimated at £5/tCO_2 per 500 km of pipeline (Fasihi, Efimova and Breyer 2019); the remoteness of the Lochaber site makes this route particularly costly. Against this landscape, on-site mineral carbonation offers a distinctive combination of permanent sequestration, marketable co-products, and avoidance of transport infrastructure—advantages that collectively justify its selection as the preferred near-term pathway for this case study.

Sixth, the climate change implications of this work extend beyond the immediate context of the Lochaber smelter. The aluminium industry accounts for approximately 1–2% of global greenhouse gas emissions, and on-site mineral carbonation could in principle be replicated across the sector's global fleet of primary smelters. The permanent mineralisation of CO_2 into stable carbonate products removes CO_2 from the active carbon cycle for geological timescales, contributing directly to climate change mitigation rather than merely delaying atmospheric release. At the Lochaber facility alone, successful deployment would abate approximately 187,200 tonnes of CO_2 per year. Scaled across similar industrial facilities, such approaches could contribute meaningfully to the deep emissions reductions required to limit global warming in line with the Paris Agreement targets.

Finally, it is worth noting the long-term technological opportunity represented by inert anode development in aluminium smelting. Commercially viable inert anodes—which would produce oxygen rather than CO_2 at the anode—would eliminate the fundamental process source of CO_2 entirely (Kvande and Drablos 2014) . Until this technology matures, mineral carbonation represents the most commercially tractable near-term pathway for smelter decarbonisation.

6.1. Study Limitations and Uncertainties

Several important limitations of this study should be acknowledged explicitly. First, CAPEX estimates are derived from published literature benchmarks rather than vendor quotations or detailed engineering design, introducing potential uncertainty of ±30–50% at this pre-feasibility stage. Second, chemical cost assumptions—particularly for NaOH at £150/tonne and HNO_3 at the same rate—are based on current European contract prices and may vary substantially with energy market conditions, as NaOH production is electricity-intensive. Third, the 27% process emission credit deduction applied to carbon revenues is drawn from IPCC literature for generic mineral carbonation systems; site-specific life-cycle assessment would be required to confirm this figure for the Ballantrae serpentinite and Lochaber process configuration. Fourth, magnesium carbonate and silica sand market prices are assumed constant over the 20-year project life; in reality, market volumes sufficient to absorb the co-product output may require demand development, and price erosion under increased supply is plausible.

Fifth, the model does not include decommissioning costs, which could affect the terminal-year cash flows. Sixth, the analysis does not account for potential changes in UK ETS policy or carbon pricing trajectory, which would have a significant influence on project viability. These limitations collectively suggest that the reported IRR of 16% and payback period of 11 years should be interpreted as indicative of financial potential under favourable assumptions, rather than as definitive investment-grade conclusions. A formal sensitivity analysis examining the effect of ±20% variation in key parameters (NaOH cost, carbon credit price, $MgCO_3$ price, and CAPEX) is recommended as a next step before project development.

7. Conclusion

This study presents a detailed techno-economic assessment of deploying an on-site ex-situ mineral carbonation plant at the ALVANCE British Aluminium smelter in Lochaber, Scotland. Two process pathways were evaluated: serpentinite rock from the Ballantrae ophiolite belt and seawater brine from adjacent Loch Linnhe.

The serpentinite route demonstrates commercially meaningful potential. With CAPEX of £152 million, annual OPEX of £62.4 million, and combined revenues from carbon credits, magnesium carbonate, and silica sand, the project achieves an 11-year simple payback period and an after-tax IRR of 16%—consistent with viable infrastructure investment. The proximity of the Ballantrae serpentinite resource (theoretical CO_2 storage potential exceeding 900 million tonnes) ensures long-term feedstock security. On-site location eliminates CO_2 transport costs, and material symbiosis with neighbouring industries further strengthens the business case.

The seawater route does not achieve financial viability within a 20-year project horizon under current assumptions. The structural imbalance between NQ-only revenue and high alkali consumption costs, combined with the absence of silica by-product, produces persistently negative net savings. Substantial reductions in alkali costs or significant uplifts in NQ market pricing would be required before this route could compete.

More broadly, this analysis demonstrates that on-site mineral carbonation in industrial cluster settings is a financially grounded and scalable pathway for near-term CO_2 abatement in hard-to-decarbonise sectors. With carbon pricing policy continuing to strengthen and demand for sustainable construction materials growing, the economics of such schemes are likely to improve over time (Riffat, S., et al. 2026) . The integration of AI-based optimisation tools for energy systems further offers potential to enhance the operational efficiency of such plants in real-world deployment (Razak, et al. 2025) . The serpentinite route at Lochaber offers a viable mechanism to abate over 187,200 tonnes of UK industrial CO_2 per year while generating a positive financial return—demonstrating that large-scale decarbonisation and economic sustainability need not be mutually exclusive objectives.

From a climate change perspective, the significance of this work lies in demonstrating a financially credible route to permanent CO_2 removal from a hard-to-abate industrial sector. Unlike approaches that merely defer emissions or shift them elsewhere in the supply chain, mineral carbonation locks CO_2 into thermodynamically stable carbonate minerals for geological timescales. The study thereby contributes to the evidence base for CCUS as a climate mitigation tool, consistent with the IPCC's finding that achieving net-zero targets will require both demand-side reductions and active carbon removal.

Several important limitations must be recognised. The financial projections are based on literature-derived cost benchmarks, and CAPEX uncertainty of ±30–50% is typical at this pre-feasibility stage. Chemical cost assumptions for NaOH are sensitive to energy price volatility. Magnesium carbonate and silica market prices are held constant, whereas real market conditions would involve demand development and potential price erosion. The 27% process emission deduction applied to carbon credit revenues requires validation through a full life-cycle assessment of the specific Ballantrae–Lochaber system. UK ETS policy risk also remains a material uncertainty. Accordingly, the reported IRR of 16% and payback period of 11 years should be interpreted as indicative of financial potential under favourable assumptions, rather than investment-grade conclusions. Key next steps before project development would include: (1) a formal sensitivity analysis across key cost and revenue variables; (2) a site-specific life-cycle assessment; (3) vendor-level CAPEX quotations based on detailed process design; and (4) market feasibility assessment for co-product offtake.

Author Contributions

Conceptualization, A.S.; methodology, A.S.; formal analysis, A.S.; investigation, A.S.; resources, A.S.; data curation, A.S.; writing—original draft preparation, A.S.; writing—review and editing, A.S. and W.Z.; supervision, W.Z.; project administration, W.Z. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflict of Interest Statement
The authors declare no conflicts of interest.

Data Availability Statement
All data supporting the reported results are derived from published literature as cited in the references. No new primary datasets were created during this study.

Ethics Statement
The authors confirm that this study does not involve human participants or animal experimentation. All data analyzed in this work are derived from publicly accessible datasets and previously published studies. Accordingly, ethical approval and informed consent were not required.

AI-Assisted Editing Statement
The authors used an AI-based language editing tool for improving grammar, clarity, and readability. No part of the scientific content, analysis, or conclusions was generated by artificial intelligence. The authors fully reviewed and took responsibility for the final version of the manuscript.

Acknowledgment
The authors wish to thank the Department of Engineering at Nottingham Trent University for institutional support and access to research resources. Gratitude is also extended to the British Geological Survey for publicly available data on the Ballantrae serpentinite deposits.

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