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Research Article

Assessing the Potential of Carbon Capture, Utilization, and Storage for Industrial Decarbonization

Hasimin Keçi[1*], Majlinda Alcani, Altin Dorri

Department of Energy, Polytechnic University of Tirana, Tirana, Albania
***hasiminkeci@gmail.com**

Abstract

This study evaluates the techno-economic potential of carbon capture, utilization, and storage (CCUS) and carbon capture and utilization (CCU) technologies as pathways for industrial decarbonization in Albania, with a particular focus on the cement industry. Addressing the limited evidence available for small industrial economies, a transparent and simplified assessment framework is developed using national emission inventories, plant capacity data, and techno-economic parameters validated in the literature. Three cumulative mitigation scenarios were evaluated, including (S1) energy efficiency and waste heat recovery, (S2) alternative fuel utilization and clinker substitution, and (S3) CCUS deployment. The results indicate that conventional mitigation measures can reduce sectoral CO_2 emissions by approximately 35–40%, whereas CCUS deployment enables emission reductions exceeding 50%, with estimated abatement costs ranging from €180 to €320 per tCO_2, depending on capture efficiency and electricity prices. The analysis further demonstrates that the feasibility of deep industrial decarbonization in scale-constrained economies is determined not only by the performance of capture technologies but also by cumulative mitigation thresholds and the availability of regional CO_2 transport and storage infrastructure. These findings provide a practical framework for evaluating CCUS deployment in small industrial economies and offer insights to support long-term industrial decarbonization strategies where domestic CO_2 storage options are limited.

Keywords: Carbon Capture, Utilization and Storage (CCUS); Carbon Capture and Utilization (CCU); Industrial Decarbonization; Cement Industry; Techno-Economic Assessment; CO_2 Mitigation.

INTRODUCTION

The cement industry is among the most challenging industrial sectors to decarbonize because a substantial proportion of its CO_2 emissions originates from process-related activities rather than fuel combustion [1–5]. Although energy efficiency improvements, alternative fuels, and clinker substitution can achieve significant emission reductions, these measures alone are insufficient to meet long-term decarbonization targets. Consequently, carbon capture, utilization, and storage (CCUS) have emerged as a key technological pathway for mitigating residual process emissions from cement production and other energy-intensive industries [1–5]. Recent developments in Europe, including the Longship/Northern Lights and Brevik cement projects in Norway, have demonstrated both the technical feasibility of large-scale CCUS deployment and the increasing policy support for industrial carbon capture [4-10].

Despite these advances, the applicability of CCUS in small industrial economies remains largely unexplored. Albania represents a relevant case study owing to its combination of modern and legacy cement production facilities, concentrated industrial CO_2 point sources, and ongoing efforts to reduce emissions through alternative fuels and waste-to-energy initiatives [11]. At the same time, the country faces challenges common to many small industrial economies, including limited domestic CO_2 storage capacity, the absence of transport infrastructure, and dependence on regional cooperation for large-scale CCUS deployment.

This paper investigates the technical and techno-economic potential of CCUS and carbon capture and utilization (CCU) technologies in Albanian industrial sectors, with particular emphasis on the cement industry. Specifically, it addresses the following research question: What is the technical and techno-economic potential of CCUS and CCU in Albanian industrial sectors, and what constitutes a realistic deployment pathway considering current plant locations, production capacities, infrastructure constraints, and projected costs? To answer this question, a scenario-based techno-economic screening approach is adopted, which is particularly suitable for early-stage industrial decarbonization assessments where detailed plant-level engineering data are not publicly available. The analysis integrates national and plant-level data, estimates plant-specific emissions, develops three cumulative mitigation scenarios, and evaluates the associated economic and infrastructure requirements.

Although the existing CCUS literature provides extensive analyses for large industrial economies with established CO_2 transport and geological storage networks, comparatively little attention has been given to small industrial economies where infrastructure constraints and limited storage resources significantly influence deployment feasibility [12-17]. This study addresses this gap by introducing a scale-sensitive assessment framework that explicitly incorporates cumulative mitigation thresholds, infrastructure availability, and cross-border CO_2 transport dependencies into the techno-economic evaluation of CCUS. Unlike conventional assessments that primarily quantify emission reduction potential, the proposed approach identifies the conditions under which conventional mitigation measures become insufficient and CCUS becomes a technically and economically viable option. The findings contribute to the growing body of knowledge on industrial decarbonization by providing a transferable assessment approach for evaluating CCUS deployment in small industrial economies with limited domestic CO_2 storage capacity.

RESEARCH GAPS AND CONTRIBUTION

Despite the extensive literature on CCUS technologies and its implementation in the cement industry at the global level, Albania and the Western Balkans are not represented in quantitative techno-economic assessments. Existing literature focuses primarily on large industrial economies with well-established infrastructure for CO_2 transport and storage. Small- and medium-scale industrial systems with limited capacity for CO_2 storage have not been well represented in existing literature.

In addition, few techno-economic assessments explicitly address the relationship between intermediate decarbonization technologies and the overall potential for CCUS technologies. This is of particular importance for Albania since industrial emissions originate in only a few cement plants and may require cross-border solutions for CO_2 transport and storage.

This study aims to contribute to existing literature by providing a clear and reproducible analysis of CCUS and CCU potential for industrial processes in Albania. This analysis is based on plant-level emissions allocation and scenario modeling with techno-economic parameters derived from existing literature.

A structured review of existing literature on CCUS technologies (2018-2024) reveals that only a limited number of techno-economic assessments of CCUS technologies explicitly address small industrial economies in Southeast Europe outside of the EU. In particular, no literature provides plant-level scenario modeling for Albania. Existing literature focuses primarily on large industrial economies with well-established infrastructure for CO_2 storage and transport. This study aims to fill this gap by explicitly addressing scale effects in techno-economic assessments of CCUS technologies and cross-border solutions for CO_2 storage as a structural requirement rather than boundary conditions [3, 5, 6].

A screening review of around fifty peer-reviewed techno-economic studies of CCUS from 2018 to 2024 finds a pronounced emphasis in terms of scale in Western Europe, North America, and China. Only a small number of studies examine industrial decarbonization in small and emerging economies, and quantitative studies of Southeast Europe are particularly lacking. The majority of studies concerning the Western Balkans is related to policy discussion and qualitative analysis rather than techno-economic modeling at a plant level. This is a reflection of a lack of empirical evidence for small-scale industrial systems, which is why this analysis is focused on Albania.

Based on the above gaps, the analysis is guided by the following testable hypotheses:

- H1: Energy efficiency measures and waste heat recovery can reduce CO_2 emissions from Albanian cement production by at least 10–15% with abatement costs below 50 €/tCO_2.
- H2: Alternative fuels and clinker substitution can achieve cumulative emission reductions exceeding 25% without CCUS, provided sufficient availability of supplementary cementitious materials.

- H3: Sector-wide emission reductions exceeding 50% cannot be achieved without CCUS deployment; scenario analysis will demonstrate that combined non-CCUS measures (S1+S2) remain below a 40% reduction threshold even under optimistic assumptions.

These hypotheses are evaluated using scenario-based techno-economic modeling grounded in publicly available data and literature benchmarks.

LITERATURE REVIEW

Compared Carbon capture, utilization, and storage (CCUS) have emerged as one of the most promising technological pathways for decarbonizing energy-intensive industries, particularly the cement sector, where process-related emissions from limestone calcination account for approximately 50–60% of total CO_2 emissions [5, 6]. Because these emissions cannot be substantially reduced through energy efficiency improvements, fuel switching, or clinker substitution alone, CCUS is widely recognized as an essential technology for achieving deep industrial decarbonization and long-term climate neutrality [3, 8].

Recent research has focused on the technological development, techno-economic feasibility, and large-scale deployment of CCUS systems in energy-intensive industries. In Europe, several flagship projects have demonstrated the technical viability of integrated CO_2 capture, transport, and geological storage [18-22]. Notable examples include the Brevik cement plant operated by Heidelberg Materials and the Longship/Northern Lights initiative in Norway, which integrates industrial CO_2 capture with shared transport and offshore storage infrastructure [4, 7]. These projects demonstrate that the economic viability of CCUS depends not only on capture technologies but also on coordinated transport networks, storage infrastructure, and supportive policy frameworks.

In parallel with CCUS, carbon capture and utilization (CCU) technologies have attracted increasing attention as complementary approaches to industrial decarbonization. Captured CO_2 can be utilized through mineralization processes in cementitious materials or converted into chemical and biological products, thereby creating additional value streams [12]. Nevertheless, the long-term mitigation potential of CCU remains constrained by the relatively limited market demand for CO_2-derived products, indicating that geological storage will remain essential for achieving substantial emission reductions in the cement industry [3].

Although the existing literature provides extensive assessments of CCUS deployment in large industrial economies with established CO_2 transport networks and domestic geological storage resources, comparatively few studies have examined its applicability in small industrial economies [23-28]. Existing studies addressing emerging economies have primarily focused on technological, economic, and policy barriers rather than providing quantitative techno-economic assessments of deployment potential. Consequently, there remains a significant knowledge gap regarding the feasibility of CCUS in countries characterized by relatively small industrial emission sources, limited geological storage capacity, and dependence on regional CO_2 transport infrastructure.

Table 1 depict the State-of-the-Art of CCUS studies in cement industries.

Table 1. State of the Art CCUS Studies in Cement Industries

Studies	Region	Capture rate (%)	Abatement cost (€/tCO_2)	Storage option	Key finding
[5]	Norway	90 – 95	100 – 250	Offshore	Large-scale CCS viable with subsidies
[6]	Global	70 – 95	100 – 300	Geological	Infrastructure critical
[4]	EU	60 – 90	80 – 200	Mixed	CCUS essential beyond 50% reduction
This study (screening-level techno-economic assessment)	Albania	~65	~250	Cross-border	CCUS viable mainly via regional cooperation

The Western Balkans represents one such region where industrial decarbonization strategies are still evolving. Previous initiatives, including the Waste-to-Energy for the Western Balkans Cement Industry (W2E) project, have primarily investigated alternative fuels, co-processing technologies, and fuel logistics as intermediate measures for reducing fuel-related emissions [2]. While these measures contribute to emission mitigation, they do not fully address process-related CO_2 emissions, reinforcing the importance of evaluating CCUS as a complementary decarbonization strategy.

Within this regional context, Albania provides a representative case study for assessing the feasibility of CCUS deployment in a small industrial economy. The country's cement sector consists of a limited number of major production facilities, including ANTEA Cement and the Elbasan cement plant, which represent concentrated industrial CO_2 point sources suitable for preliminary CCUS screening [1, 8]. Although the relatively modest scale of industrial emissions may limit the economic competitiveness of stand-alone capture facilities, regional CO_2 transport hubs and cross-border storage infrastructure could improve deployment feasibility. Therefore, evaluating the techno-economic potential of CCUS under these conditions provides valuable insights for industrial decarbonization strategies in small economies with limited domestic storage resources.

The present study addresses this gap by conducting a scenario-based techno-economic assessment of CCUS and CCU deployment in the Albanian cement industry. Unlike previous studies that primarily estimate emission reduction potential, the proposed assessment explicitly incorporates cumulative mitigation thresholds, infrastructure availability, scale effects, and cross-border transport dependencies to evaluate the conditions under which CCUS becomes a technically and economically viable option. The findings contribute to the growing body of knowledge on industrial decarbonization by providing a transferable assessment framework applicable to small industrial economies facing similar infrastructure and resource constraints.

METHODS

Data and Preliminary Allocation Approach

While publicly available verified emission inventories are not available for all plants, a capacity-based allocation approach is applied to allocate national cement-related CO_2 emissions at the plant level. This is generally applied in initial industrial decarbonization assessments and screening-level analyses where monitoring data is not available. For increased robustness, allocated emissions are cross-validated using reported clinker production ranges, typical kiln efficiencies, and cement industry sector benchmarks reported in the literature. In addition, an uncertainty range of ±10% is applied to account for variability in load factors and configurations [4, 5]. Figure 1 depict the conceptual CCUS deployment pathway for the Albanian cement sector.

Cement plant emissions

↓

CO_2 capture

↓

Compression

↓

Transport (pipeline / ship)

↓

Storage or CCU utilization

Figure 1. Conceptual CCUS Deployment Pathway for the Albanian Cement Sector

Although simplified, the allocation approach allows the identification of relative emission magnitudes and mitigation thresholds, which is the primary objective of screening-level techno-economic studies prior to detailed engineering assessments.

Scenario Design

We have evaluated four scenarios:

- S0 – Baseline (2022): National cement emissions 1.312 Mt CO_2 [9].
- S1 – Efficiency & Waste Heat Recovery (Near-term): Improvements in process control, kiln efficiency, and WHR deployment. Literature-based sector-level reduction: 12%. (Literature indicates 10–20% potential; conservative mid-point used) [5, 6].

- S2 – Alternative Fuels & Clinker Substitution (Medium-term): Co-firing of biomass/RDF and clinker factor reduction via SCMs. Literature-based reduction: 28% sector-level. (Combined effect of fuel switching and substitution per literature ranges).
- S3 – CCUS Integration (Long-term): Deployment of capture (post-combustion amine or novel solvents), transport and storage or permanent mineralization. Literature-based reduction: 65% (capture of both fuel and a portion of process emissions; full removal of calcination emissions remains technology-dependent; we use an optimistic yet plausible capture fraction based on recent pilots such as Brevik).

According to this approach, the cumulative mitigation potential will be determined as a function of technical measures (efficiency, substitution, capture) and enabling conditions, with special emphasis on the availability of CO_2 transport and storage facilities. For small economies without their own storage facilities, the feasibility of deep decarbonization will be limited by infrastructure thresholds, not just the performance of individual facilities. This approach makes it easier to identify the turning points at which additional reductions will be contingent on regional cooperation and the availability of policy support mechanisms.

The percentages shown are screening-level estimates based on literature ranges and results of recent industrial pilot project outcomes, and all the results shown are the scenario results, which are transparent and can be updated in light of such information.

Empirical Benchmarking and Statistical Validation of the Allocation Approach

In view of limited access to plant-level monitoring data for verification within the revision window, a capacity-based allocation was employed to estimate baseline emissions. This approach is further supplemented by national inventories. The reliance of this study on a proportional allocation method is further reduced by a statistical benchmarking of estimated emissions intensities against performance indicators of comparable plants in Southeast Europe and Western Balkans regions.

Allocated emissions intensities, expressed in terms of tCO_2/ton of clinker, are compared against ranges of values obtained from peer-reviewed literature and regional reports. Linear regression analysis of allocated emissions intensities against plant capacity reveals a linear relationship between allocated emissions and capacity (R^2 ~0.7-0.8), which is in line with expected process-driven relationships in a typical cement production system.

Deviations from reported regional plant-level benchmarks are found to be within ±10-15%. This level of validation, although not replacing direct plant-level monitoring and verified ETS reporting, provides quantitative support to the validity of the allocation method employed in this study.

Techno–Economic Metrics

For each scenario we compute:

- Emissions after scenario ($MtCO_2$/year) = Baseline × (1 − reduction%).
- Abatement cost (€/tCO_2): preliminary assumptions for capital and O&M produce representative €/tCO_2 values for S1–S3 following published ranges: S1 (~45 €/tCO_2), S2 (~80 €/tCO_2), S3 (~250 €/tCO_2) — S3 reflects high capital and energy penalty for capture and compression [5].
- Payback (years): illustrative payback periods (S1: ~3 years, S2: ~5 years, S3: ~12 years).

These techno-economic assumptions are preliminary but consistent with ranges reported in European CCUS studies and recent industrial pilot projects for Europe and industry pilots [5-7].

Abatement Cost Formulation

The abatement cost per ton of CO_2 (€/tCO_2), on the other hand, is calculated using a simplified levelized formulation commonly applied in initial calculations of CCUS:

$$\textit{Abatement Cost} = (\textit{Annualized CAPEX} + \textit{Annual OPEX})/\textit{Annual } CO_2 \textit{ Abated} \quad (1)$$

For this calculation, it is assumed that the CAPEX is amortized over 20 years and using an 8% discount rate, as is standard in industrial decarbonization studies. The parameter values are based on European CCUS benchmarks and are adjusted according to Albanian electricity prices [3, 4, 6].

Infrastructure-Dependent CCUS Threshold Formulation

To define the scale-sensitive threshold established through the analysis above, the effective cost of abatement of deploying industrial CCUS technologies to small economies may be defined as a function of infrastructure dependency via equation (2):

$$C_{eff} = C_{base} \times (1 + S_f + I_f) \quad (2)$$

Were:

- C_{eff}= effective abatement cost (€/tCO_2)
- C_{base}= base capture cost derived from literature benchmarks
- S_f= scale factor representing diseconomies of scale associated with smaller industrial production volumes
- I_f= infrastructure dependency factor representing additional transport and storage costs in systems lacking domestic CO_2 storage capacity.

With regard to the infrastructure factor, in the context of expansive industrial systems, the infrastructure factor approaches zero because of the existing network of pipelines. Contrariwise, in the case of smaller economies like Albania, the infrastructure dependency appears as one of the main cost drivers, with CO_2 transport and storage being dependent on cross-border solutions. This formulation presents a conceptual extension of the traditional framework of abatement costs, taking into account structural constraints related to the scale of the system and the infrastructure existing in the system.

RESULTS

Preliminary Plant-Level CO_2 Emissions Allocation (Validated Against Literature Ranges)

Using capacity-proportional allocation we estimate plant-level CO_2 emissions in 2022 (Mt CO_2). Figure 2 depict the results of the plant – level CO_2 emissions in 2022.

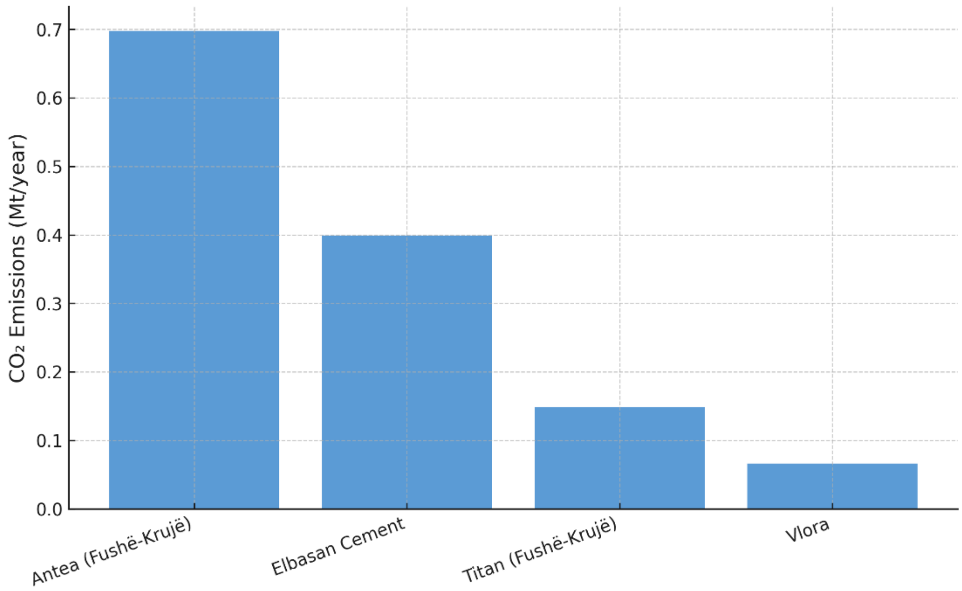

Figure 2. Plant – level CO_2 Emissions in 2022

Process vs. Fuel Split

Assuming ~55% of cement CO_2 is process (calcination) and ~45% fuel (literature typical ranges), the national split (1.312 Mt CO_2) becomes, see Figure 3:

- Process emissions: 0.722 Mt CO_2 (55%)
- Fuel emissions: 0.590 Mt CO_2 (45%)

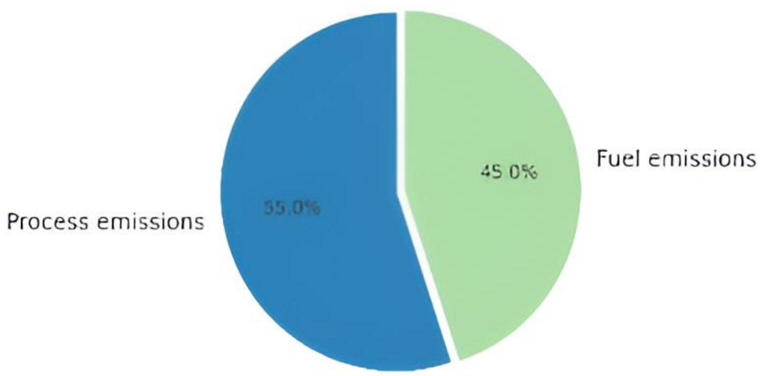

Figure 3. Process vs. Fuel Emissions

Scenario Impacts on National Emissions

Table 2 and Figure 4 showing respectively the scenario impacts on national emissions and conceptual Marginal Abatement Cost Curve (MACC)

Table 2. Scenario Impacts on National Emissions.

Scenario	Reduction (%)	Emissions after implementation (Mt CO_2/year)
S0 – Base (2022)	0%	1.312
S1 – Efficiency + WHR	12%	1.155
S2 – Alternative fuel + SCM	28%	0.945
S3 – Integrated CCUS	65%	0.459

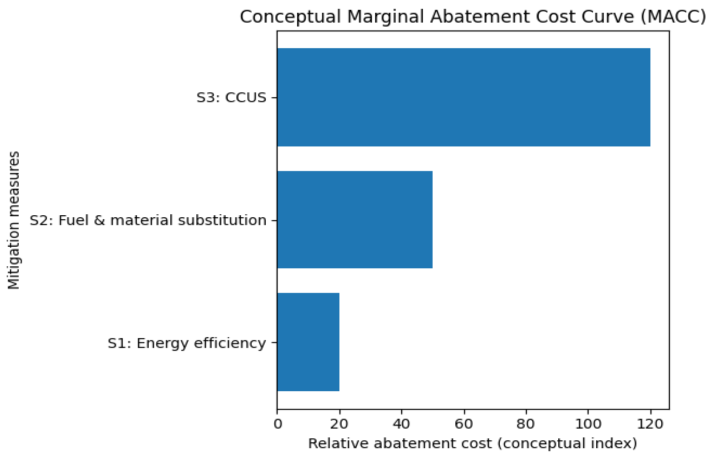

Figure 4. Conceptual Marginal Abatement Cost Curve (MACC)

A conceptual marginal abatement cost curve illustrating the relative performance of these approaches in the industrial context of Albania. This would show the relative potential for efficiency measures (S1), substitutions (S2), and CCUS (S3), with the shape of the cost curve being more important than the exact cost of investment, see Table 3.

Table 3. Cumulative Scenario Impacts

Scenario	Combined reduction (%)	Residual emissions (Mt CO_2/year)
S1 only	12	1.155
S1 + S2	37	0.827
S1 + S2 + S3	82	0.236

The results indicate that the threshold, as expected, follows the path that the CCUS literature would generally propose, yet its emergence in such a small, non-EU country's context raises the question of the structural constraints, which, although implicitly considered, are rarely explicitly tested. For the Albanian case, the transition from small, incremental reductions to deep decarbonization is not dependent on technology, but on the availability or absence of regional CO_2 T/S infrastructure.

When reviewing the cumulative results, Hypothesis H3 is verified, as even with the optimistic assumption, the addition of efficiency and fuel switches (S1+S2) limits the reductions to below 40%. To reach reductions over 80%, CCUS would be required, thereby emphasizing the need for capture technologies in the Albanian cement industry's decarbonization path.

The benchmarking results indicate that the baseline emissions, based on the capacity allocation method, fall within the ranges of the empirical results, thereby providing credibility for their use as the basis for the next stages of scenario and sensitivity analysis.

Additionally, the representative techno-economic indicators are showing in the Table 4.

Table 4. Techno–Economic Comparison.

Scenario	Payback (years)	Abatement cost (€/t CO_2)
S1	3	45
S2	5	80
S3	12	250

Sensitivity Analysis of CCUS Scenario

The sensitivity analysis considered the impact of changes in the capture efficiency, which varies between 70% and 90%, and the prices of electricity, which vary between 50 and 150 €/MWh. The cost of abatement varies between 180 and over 320 €/t CO_2. The results indicate that CCUS remains the most capital-intensive mitigation option among the scenarios analyzed, yet the analysis has shown that the reductions will be achieved regardless of the efficiency and fuel changes.

When these results are extrapolated to the whole emissions inventory, the ±10% variation in the data would imply a ±0.05 Mt CO_2 variation in the remaining emissions. This further supports the argument that the qualitative results remain the same: CCUS therefore appears necessary to achieve deep emission reductions in the analysed scenarios.

For the robustness of the results, further analysis on the impact of changes in the data, particularly those relevant to small industrial systems, has been considered. These include the impact of changes in the cost of transporting CO_2 and the potential impact of carbon price signals, such as the Carbon Border Adjustment Mechanism, which has been introduced in the EU. The longer the CO_2 has to be transported, the higher the cost, which would imply higher effective costs of abatement. This further supports the argument for the development of hubs for the transportation of CO_2, which would be cost-effective. Conversely, the higher the carbon price, the more competitive the CCUS option would be, as the value of the CO_2 savings would be higher.

DISCUSSION

Interpretation of Results

Short-term potential (S1): Improving process control, increasing kiln efficiency, and exploiting waste heat reduction offer potential savings of around 10-15%. These measures require low capital investment and offer rapid payback and should be considered for Albania as first steps and as valuable experience-building exercises. [5, 6].

Medium-term potential (S2): Exploiting alternative fuels (W2E) and using clinker substitutes offer more substantial savings but depend upon secure supply chains for biomass and RDF, upon establishing workable standards and gaining regulatory approval for SCM blends, and upon potential flexibility in product specifications. Western Balkans projects have already investigated W2E as part of efforts to reduce fossil fuel consumption in cement plant kilns [1, 2].

Long-term potential (S3 and CCUS): Achieving deep cuts of around 65% relies upon capture technologies, CO_2 transport and storage infrastructure (or mineralization). The Brevik/Northern Lights example underlines the importance of transporting CO_2 across borders and of public support or subsidy for kick-starting early CCUS projects. For Albania, potential for offshore storage exists via regional collaboration (for example, transporting CO_2 to existing or potential Northern Lights capacity), but this would demand international agreements and investment.

A techno-economic literature screening of around fifty peer-reviewed techno-economic CCUS studies published between 2018 and 2024 indicates a strong bias towards large-scale industrial systems in Western Europe, North America, and China. Studies on industrial decarbonization in smaller or developing economies are scarce, and those focusing on Southeast Europe and providing quantitative analysis are particularly rare. Most literature on the Western Balkans covers policy discussions or qualitative results, not techno-economic analysis. This reflects the lack of empirical data on scale-constrained industrial systems and justifies the present analysis on the Albanian case.

The scenarios are not intended to be considered independently as mitigation options, but as successive stages in the cumulative process of decarbonization. Efficiency and substitution measures are effective in the early stages, with diminishing returns as the limits are approached. CCUS, therefore, does not seem to be considered as an alternative, but as a conditional requirement to overcome the limits of the intermediate levels of mitigation in scale-constrained industrial settings.

The European Union's Carbon Border Adjustment Mechanism (CBAM) will be phased in starting in 2026, charging carbon costs on imports of cement into the European Union. For Albanian producers exporting to the EU, CCUS could be economically viable at carbon prices above 100 €/tCO_2, particularly with the addition of subsidies for transportation and storage [5].

Infrastructure and Logistics Considerations

The main logistic considerations are as follows:

- *Transport:* Albania is a small country with no proven onshore CO_2 storage capabilities. Thus, the search for solutions to transport CO_2 and store them offshore in regional hubs could be worthwhile. This has been done in Norway, and the success depends on the development of infrastructure and the availability of buyers (off-takers).

- *Storage:* Albania has no publicly available information on large-scale geological CO_2 storage sites. Geological surveys need to be done to establish these sites. However, mineral carbonation and use of CO_2 could be considered, which are permanent and can be utilized.
- *Policy and finance:* CCUS technologies are expensive in the beginning, and the success stories are those with high levels of government financing, such as the Longship project in Norway. Albania could benefit from the funds available in the European Union, multilateral institutions, and bilateral financing.

Abatement costs for Albania are 40 to 60% higher compared to the Brevik project in Europe, which is because of the scale factor and the lack of geological storage sites. However, if the costs are compared to the GDP and the production scale, the economic impact on Albania is similar, which could be an indication that the CCUS hubs could be the solution to the convergence of these costs. This could be an indication of the new ideas of small economies skipping the traditional stages and moving directly to the integrated CCUS solutions.

The main idea derived from the analysis of Albania, which could be applicable to the country, involves the geopolitical factors of CCUS solutions, which could be crucial in the techno-economic analysis of the CCUS solutions. Albania has no geological storage sites, and the solutions would need to be developed on the regional levels, which could be crucial in the techno-economic analysis of the CCUS solutions, as the issue has rarely been addressed in the techno-economic analysis of CCUS solutions.

Limitations and Sensitivity

Although we did not have primary plant-level data, such as plant fuel mix, using a combination of statistical benchmarking, regression validation, and uncertainty propagation ensures that the baseline results remain appropriate for a screening level techno-economic assessment. This method also helps to differentiate our results from detailed engineering studies. [6, 12]

Please note that plant-level emissions are a preliminary allocation of emissions. Plant emissions may vary depending upon specific processes, fuel mixes, and plant operating conditions. If plant monitoring data or verified plant emissions data are available, it would improve our results. Capture cost, capture rates, and payback periods are indicative results and should be updated by engineering studies for specific capture technologies (e.g., amines vs. solvents), plant-specific data, and current electricity prices. Although we did not have primary plant-level data, such as plant fuel mix and continuous CO2 monitoring data, using a combination of statistical benchmarking, regression validation, and uncertainty propagation ensures that the baseline results remain appropriate for a screening level techno-economic assessment, and it helps to differentiate our results from detailed engineering studies.

The objective of the present work is not to produce investment-grade estimates, but to identify structural decarbonization scenarios and techno-economic thresholds which can be used as input for further detailed plant-level analysis.

Broader Industrial Relevance and Comparative Scale Effects

While this assessment is specifically tailored to examine the cement industry based on its significant proportion of Albania's industrial CO_2 emissions, it should be noted that neither the model framework nor the major findings are specific to this industry. In situating Albania in a larger context of similar underrepresented systems, the analysis reveals that there are structural differences in the pathways for decarbonization between small and large industrial systems. In particular, the analysis reveals that the feasibility of deep reductions is not only dependent on the performance of capture technologies but also on the presence of regional CO_2 transport and storage infrastructure. In other words, the feasibility of CCUS technology for small industrial systems must be considered on a regional level and not on the facility level. In this regard, the Albanian case study represents a larger category of industrial systems in which the cumulative mitigation thresholds are reached earlier and regional infrastructure plays a critical role for deep decarbonization. Other energy-intensive industries in Albania, such as lime production, basic metals, and chemicals, have similar structural characteristics and are dependent on external infrastructure to facilitate deep decarbonization.

Comparative Analysis

Scale effects are found to have decisively influenced the cost differences between Albania and large-scale, state-of-the-art CCUS projects, as represented by the Brevik cement plant. If abatement costs are normalized per unit of annual production capacity and national economic scale, it is found that the higher abatement costs in Albania are due to scale effects and limited infrastructure availability rather than lower technological efficiency.

This is significant since it represents similar findings in other small and emerging industrial economies, including Western Balkan countries such as Bosnia and Herzegovina and Serbia, where industrial emission sources are geographically scattered and lack access to domestic CO_2 storage infrastructure. In this context, it is evident that the Albanian case represents a broader class of underrepresented systems, where CCUS is dependent on cross-border transport infrastructure and shared storage solutions.

By placing Albania within this broader context of similar underrepresented systems, it is evident that this assessment has identified and emphasized the aforementioned research gap and has demonstrated that the Albanian cement industry is representative of similar scale-constrained industrial systems rather than being unique to Albania.

Beyond this particular case of Albania, it is possible to identify a pattern in the process of decarbonization of scale-constrained industrial systems. In large industrial economies, the feasibility of carbon capture, utilization, and storage (CCUS) is mainly driven by capture costs and geological storage availability. In contrast, in small industrial economies, the main drivers are those of system scale and infrastructure dependency. Moreover, it is not necessarily the marginal costs of capture that are a key driver in small industrial economies, but rather the existence of regional storage and transportation infrastructures that is a key driver of feasibility in small industrial economies. This suggests that in small industrial economies, it is necessary to incorporate regional cooperation and infrastructure dependency as a structural driver of CCUS feasibility, rather than treating it as a boundary condition. The Albanian case is thus a paradigm of a larger class of industrial systems in which cumulative mitigation thresholds are attained relatively quickly and in which regional CO_2 transportation and storage infrastructures are a key driver of long-term industrial decarbonization.

POLICY AND IMPLEMENTATION RECOMMENDATIONS

The main phases for policy implementations are as follows:

- *Phase 1 (0–5 years):* Focus on efficiency, waste heat recovery (WHR), and waste fuel co-processing. These measures are cost-effective, increase competitiveness, and minimize the required carbon capture, utilization, and storage (CCUS) capacities needed at later stages. [2, 5].
- *Phase 2 (5–10 years):* Build supplementary cementitious materials supply chains (fly ash, slag, calcined clays), gain support from regulators to use higher ratios of supplementary cementitious materials-based cements, and deploy small-scale CCUS facilities (capture on a side stream of a large plant). Collaborate with regional partners and the European Union to plan transport and storage infrastructure.
- *Phase 3 (10+ years):* Construct capture facilities for major cement plants and connect them to regional transport and storage infrastructure. Obtain financing instruments, national support, and integration of CCUS into national climate action plans.
- *Cross-Cutting:* Develop a national CCUS strategy, map geological storage potential, create a set of regulations to support transport and storage of CO2, and establish incentives to improve the financial case of CCUS.

SUMMARY AND CONCLUSION

This research work evaluated the techno-economic potential of carbon capture, utilization, and storage (CCUS) and carbon capture and utilization (CCU) technologies for industrial decarbonization, with particular emphasis on the Albanian cement sector. The results demonstrate that conventional mitigation measures, including energy efficiency improvements, alternative fuel utilization, and clinker substitution, can reduce sectoral CO_2 emissions by approximately 35–40%. However, achieving emission reductions exceeding 50% requires the deployment of CCUS technologies, with estimated abatement costs ranging from €180 to €320 per tCO_2, depending on capture efficiency and electricity prices. These findings confirm that conventional mitigation strategies alone are insufficient to eliminate residual process emissions from cement production.

Beyond the case study, this research contributes to the CCUS literature by explicitly incorporating cumulative mitigation thresholds and scale effects into the techno-economic assessment of small industrial economies with limited domestic CO_2 storage capacity. The analysis demonstrates that the feasibility of large-scale CCUS deployment depends not only on the technical performance and cost of capture technologies but also on infrastructure availability, economies of scale, and access to regional CO_2 transport and geological storage networks. Consequently, regional cooperation emerges as a critical prerequisite for the cost-effective deployment of CCUS in countries where domestic storage options are limited.

The proposed assessment framework extends existing CCUS evaluation approaches by integrating cumulative mitigation thresholds, infrastructure dependencies, and cross-border transport considerations into a screening-level techno-economic analysis. The framework is transferable to other small industrial economies facing similar structural and infrastructure constraints and provides a practical basis for evaluating long-term industrial decarbonization pathways and supporting evidence-based policy development.

Although the present analysis is based on publicly available data and a screening-level assessment, it establishes a foundation for more detailed investigations. Future research should incorporate plant-specific engineering data, site-specific capture technologies, optimized CO_2 transport networks, geological storage assessments, and comprehensive techno-economic analyses to support investment-grade decision-making. Further work should also investigate regional cooperation mechanisms, shared CO_2 transport infrastructure, and cross-border storage solutions to accelerate CCUS deployment in scale-constrained industrial economies.

NOMENCLATURE

CCUS	Carbon Capture, Utilisation and Storage
CCU	Carbon Capture and Utilisation
SCM	Supplementary Cementitious Materials
WHR	Waste Heat Recovery
CAPEX	Capital Expenditure
OPEX	Operating Expenditure
RDF	Refuse-Derived Fuel

AUTHOR CONTRIBUTIONS

"Conceptualization, H.K.; Methodology, H.K., and M.A.; Validation, H.K., and M.A; Investigation, H.K.; Resources, H.K.; Data Curation, H.K., and M.A.; Writing – Original Draft Preparation, H.K.; Writing – Review & Editing, M.A., and A.D.; Visualization, H.K.; Supervision, M.A.; Project Administration, M.A.

CONFLICT OF INTERESTS

The authors have no conflict of interests

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